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PILOT-SCALE BOILER STUDY OF SULFUR HEXAFLUORIDE AND EMISSIONS OF CO, CO₂, O₂, AND UNBURNED HYDROCARBONS AS SURROGATES FOR VERIFICATION OF HAZARDOUS WASTE DESTRUC- TION REMOVAL EFFICIENCY

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JUNE 1989

FINAL REPORT

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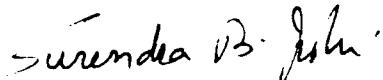
PREFACE

This report was prepared by the University of Florida Combustion Laboratory, Mechanical Engineering Department, Gainesville FL 32611, under Contract Number F08635-83-C-0136, Task 86-03, for the Air Force Engineering and Services Center, Engineering and Services Laboratory (AFESC/RDVS), Tyndall Air Force Base FL 32403-6001.

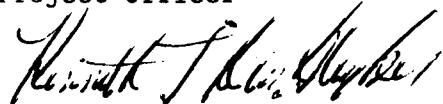
This report summarizes work done at the University of Florida Combustion Laboratory between October 1986 and June 1988. This work was performed under the direction of Dr C. L. Proctor, II, principal investigator. The contributions of D. L. Fournier, Jr., M. Hopmeier, and S. Roychoudhury are acknowledged in the completion of this report. The HQ AFESC/RDVS project officer was Mr Surendra B. Joshi.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.



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SECTION I

INTRODUCTION

A. OBJECTIVES

This research project had several objectives. One was to determine whether exhaust emissions of CO, CO₂, O₂ and total unburned hydrocarbons were related to waste destruction and SF₆ destruction in a firetube boiler environment. Another objective was to examine the use of SF₆ as a tracer for verification of waste destruction levels.

Conducting these studies in the pilot-scale unit within the laboratory allowed control over system variables which would have been difficult in a full-scale operational unit. Control of parameters such as fuel type and feed rate, waste type and feed rate, air flow, and run time could be accomplished without concern for other operating requirements, e.g., steam production and minimum exhaust temperature. Since the pilot-scale facility is similar in size and design to many smaller firetube boilers, the results are expected to be representative of those obtained from small industrial boilers.

A third objective was to examine SF₆ destruction when cofired with natural gas in both the pilot-scale facility and in a full-size industrial boiler. This was an extension of earlier laboratory work in which SF₆ was burned as a tracer in a natural gas laboratory turbulent diffusion flame (References 4, 5, and 6). The final phase of the research was conducted at the University of Florida steam plant, Boiler 5 fired on natural gas, rated at 80,000 lb/hour steam production.

The ultimate goal is to identify surrogates or tracers suitable for verifying that required waste destruction is achieved. The information from this research should help the EPA to develop surrogate methods, which could significantly reduce the expense and increase the safety and effectiveness of hazardous waste incineration systems.

B. BACKGROUND

Industrial boilers are now used extensively for hazardous waste incineration. Onsite disposal in boilers reduces transportation and disposal costs, and reduces fuel requirements by recovering the fuel value of the wastes. The liability associated with offsite transportation imposed by the cradle-to-grave provisions of the 1980 Comprehensive Environmental Response, Compensation and Liability Act is also reduced.

Recent regulations proposed by the U.S. Environmental Protection Agency (EPA) will bring industrial boilers combusting hazardous wastes under guidelines similar to those now applied to commercial incinerators (Reference 1). The tremendous expense associated with achieving compliance may economically eliminate all but the largest units. In the proposed rules, the EPA has asked for input on surrogate methods that could be used to reduce the cost of verification and perhaps provide a method for real-time monitoring of facilities combusting hazardous wastes during regular operation, after compliance testing is completed.

The United States Air Force annually generates 687,000 gallons of waste solvents and oils suitable for cofiring in industrial boilers. These wastes are currently shipped offsite for disposal at a cost of over \$2.5 million dollars. This cost is increasing exponentially and the Air Force is now investigating the option of destroying these wastes onsite in their own industrial boilers (Reference 2). Kimball (Reference 3) discusses segregation of Air Force wastes for energy recovery.

Environics Division of the Air Force Engineering and Services Laboratory at Tyndall Air Force Base funded research at the University of Florida to experimentally investigate exhaust emissions of carbon monoxide (CO), carbon dioxide (CO₂), total unburned hydrocarbons (TUHC) and oxygen (O₂) as surrogates for verifying that acceptable waste destruction levels are attained during waste combustion. Additionally, this research also examined sulfur hexafluoride (SF₆) as a tracer compound for verification of waste destruction levels.

The research was conducted in a pilot-scale 100-horsepower firetube boiler simulator constructed for this study at the University of Florida Combustion Laboratory. The wastes used were monochlorobenzene, trichloroethylene, methyl ethyl ketone, isopropanol, and toluene. Studies were also conducted at the University of Florida steam plant on SF₆ destruction in a full-scale boiler burning natural gas. The study at the steam plant began the process of expanding the research to a full-scale unit.

C. SCOPE

Section II presents a brief discussion on the regulations associated with hazardous waste incineration systems, the use of industrial boilers for waste incineration, and surrogate methods, followed by a brief review of related studies. Section III describes the experimental research project. The data analysis procedure and the results are presented in Section IV. Conclusions and recommendations are discussed in Section V.

The results of this research are promising, verifying that SF_6 is a conservative indicator of waste destruction in this facility. Excess air was also found to significantly affect both waste and SF_6 destruction. However, studies concerned with developing surrogate methods and tracers for indicating waste destruction should be extended to full-scale boilers of various size and design, combusting a variety of wastes under various operating conditions. A large data base of this type is necessary if the EPA is to propose surrogate methods that will stand up to scientific and public scrutiny.

SECTION II

BACKGROUND AND LITERATURE REVIEW

A. REGULATORY BACKGROUND

The disposal of hazardous waste has received considerable attention from the public, the scientific and research communities, and regulatory agencies. The heightened environmental concerns now demand demonstrably safe and effective methods for handling and disposing of hazardous wastes.

Studies funded by the Environmental Protection Agency (EPA) estimated that 264 million metric tons of hazardous wastes were generated in the United States in 1981 (Reference 7). Much of these wastes consists of organic solvents, of which 75 percent are liquids or dissolved in liquids (Reference 8).

Congress required the EPA to regulate the disposal of hazardous wastes with the passage of the Resource Conservation and Recovery Act (RCRA) of 1976, as amended in 1980 by the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). The Hazardous and Solid Waste Amendments (HWSA) to RCRA in 1984 severely restricted the disposal of liquid hazardous wastes in landfills. In passing the HWSA amendments, Congress was motivated by public concern about potential groundwater contamination, fugitive emissions, and the recognition that landfills are only a storage option, and not the ultimate disposal.

In response to the HWSA amendments, the EPA has identified thermal destruction as the Best Demonstrated Available Technology (BDAT) for destroying many of the wastes restricted from landfill disposal. Incineration has been widely used as a disposal option for eliminating many hazardous wastes and offers several advantages over landfills. The toxic compounds are converted to harmless, or less harmful compounds. It also provides a means for ultimate disposal and volume reduction.

Incineration is not without its own set of problems, however. Exhaust gas treatment systems are required to remove particulates, metals and halogenated compounds (e.g., hydrochloric acid). Ash, scrubber water and other discharges may remain hazardous and may require additional treatment or landfill disposal. Some wastes may be better suited to other disposal options such as chemical, physical, or biological processes (Reference 9).

A major obstacle to increased use of incineration has been strong public opposition (Reference 10). A major public concern is the lack of a real-time method for monitoring system performance. Public acceptance would likely increase if there existed a real-time method directly linked to waste destruction levels which could alert operators to take corrective action during system upsets or poor performance.

B. TRIAL BURNS

1. Destruction Removal Efficiency

Present permitting regulations require operators of incinerators to demonstrate through trial burns that a Destruction Removal Efficiency (DRE) of at least 99.99 percent is attained for selected wastes chosen as Principal Organic Hazardous Constituents (POHCs). POHCs chosen for use in the trial burn are selected to represent the most difficult-to-destroy compounds to be treated by the unit during operation. Current incinerability rankings of wastes are based on heats of combustion.

Waste streams may contain numerous compounds regulated as hazardous wastes. Testing for selected POHCs avoids the difficulty and expense of testing for each waste, assuming that, if the unit can successfully destroy the most difficult-to-destroy compounds, it will be able to destroy less stable wastes.

The DRE represents the amount of the waste thermally destroyed or removed by pollution control equipment. It is expressed as

$$DRE = (m(\text{in}) - m(\text{out}))/m(\text{in})$$

where m = mass flow of the POHC

Additional restrictions are placed on emissions of metals, hydrochloric acid (HCl), particulates, and carbon monoxide.

Factors that affect the DRE include temperature, residence time, oxygen distribution, mixing and atomization (References 9 and 11). In commercial incinerators the physical processes of atomization, evaporation, and turbulent fuel-air mixing often dominate chemical kinetics in limiting the reaction rate and the destruction efficiency (References 8 and 12.)

Proper burner and furnace design is required to prevent droplet penetration and wall impingement which can adversely affect the DRE and lead to incomplete combustion of the fuel or waste (References 13, 14 and 15). Mulholland, Srivastava and Ryan (Reference 8) estimate that one drop in ten million escaping can lead to DREs less than 99.99 percent.

The system design must promote turbulence which is required to aid heat transfer, mass transfer, vaporization and flame propagation necessary for efficient fuel-waste-air mixing (Reference 9 and 16). Excess air is required to insure oxidation of the waste; however, too much excess air can quench the reaction by acting as an energy sink, or by adversely affecting turbulent mixing in the furnace. Poor performance can also result from low temperatures caused by low calorific value of the fuel-waste mixture, high heat removal rates, and quenching by flame impingement on an aqueous jet or relatively cool surface (Reference 17).

In properly designed and operated systems, chemical kinetics become important in combustion. Temperature, residence time at that temperature, and the chemical makeup of the waste become important. Incinerators are usually designed to provide high temperatures and long residence times to ensure that any waste or intermediate combustion product surviving the flame zone is destroyed.

2. Problems with the Trial Burn System

The trial-burn method of compliance verification has several deficiencies. Trial burns are expensive and time-consuming, and the results are subject to uncertainty. Gas-sampling and analysis expenses for a trial burn can range from \$30,000 to \$150,000. Testing and sampling usually require a week to complete. Several months are required for analyzing collected samples, generating reports, and processing permits (Reference 18).

Several reasons exist for the expense and time required for trial burn analysis. It is difficult to measure the trace amounts of POHCs in the exhaust, often taxing available analytical methods. It is also difficult to accurately quantify POHC concentration in the feed stream, which may not be homogeneous. These factors add to the uncertainty of the trial-burn method.

Furthermore, data obtained at the trial burn only indicates how the unit is functioning at that time. Information is not provided on future performance fluctuation with changes in operating conditions or feed characteristics. The trial-burn method does not provide the operator with real-time information on system performance during normal operation which would allow corrective actions during performance deterioration.

Additional complications facing incinerator operators include extensive documentation, local public relations and a complicated permitting process often requiring the resources of outside consultants. Usual permitting time is 3 years, with total expenses of \$1 million not uncommon.

C. BOILER USE FOR WASTE INCINERATION

Industrial boilers have found widespread use for waste incineration. Advantages of boiler incineration over landfills and commercial incinerators include energy recovery and onsite destruction. Many wastes have sufficiently high heating values to warrant their use as alternate fuels, or cofiring with supplemental fuels (References 19 and 20). Onsite destruction also greatly reduces the liability, regulatory paperwork and expense associated with transporting the wastes offsite for treatment.

EPA studies indicate that there are over 43,000 industrial boilers of proper size and design to potentially achieve acceptable waste destruction levels (Reference 21). Of these, 5,500 are located in the chemicals, petroleum refining, and paper industries and are accessible to over 95 percent of all potentially combustible hazardous waste. Actual use is estimated to be approximately 1300 boilers disposing of 3.5 million tons of hazardous waste annually (Reference 21).

When the EPA promulgated the RCRA incineration mandates, beneficial uses of wastes for energy recovery were intentionally exempted from compliance requirements pending further study. After conducting a number of studies the EPA has decided to regulate boilers and industrial furnaces combusting hazardous wastes using guidelines similar to those applied to incinerators (Reference 1).

The added expense imposed by these new regulations could make waste disposal in industrial boilers economically feasible to only the largest producers (Reference 22). The economic elimination of a large number of industrial boilers currently disposing of hazardous wastes may place a serious strain on thermal destruction capacity in the United States, which is near maximum use (Reference 10).

D. SURROGATES

Considerable research has been conducted with the goal of identifying surrogate methods that could be used to evaluate the effectiveness of waste incineration systems. Potential benefits include lower cost and improved accuracy of trial burns. Surrogates could be used in place of POHCs at trial burns, to identify proper operating conditions for best waste destruction, or to determine if a system is suitable for waste destruction before undertaking the expense of a trial burn.

Additionally, a real-time method of monitoring system performance could greatly increase the safety and public acceptance of incineration for waste disposal. Both the EPA and industry are very interested in surrogate methods. In the proposed rules for boilers and furnaces the EPA has requested comment on using surrogate compounds in place of POHCs to demonstrate DRE during trial burns (Reference 1).

Surrogates can be combustion intermediates or tracers added to the waste feed. Emissions of CO, CO₂, O₂, and total unburned hydrocarbons (TUHC) are combustion by-products which may be related to waste destruction levels and might therefore be suitable for use as surrogates. Another option is to continuously monitor the destruction of an added tracer not normally found in the feed streams. The level of destruction of this compound could be related to the destruction level of the hazardous wastes and provide a conservative indicator of waste destruction.

1. Combustion Byproducts as Surrogates

Current incinerator regulations and the proposed rules for boilers restrict emissions of carbon monoxide. Emissions of CO are often used to optimize combustion efficiency and the restriction on CO emissions is to ensure that units burning hazardous wastes are operating at high combustion efficiency.

A number of studies have examined the relationship between exhaust CO emissions and waste DRE. Most have found that CO emissions do not correlate well with DRE, although high CO concentrations tend to precede the onset of DRE degradation (References 23, 24, 25, 26, 27, 28, 14, 29, 30 and 31) found moderate correlation of CO and the ratio of CO to CO₂ with DRE in a pilot scale study.

Low CO is an indicator of the CO to CO₂ conversion process, which is the last rate-limiting oxidation process. Oxidation of POHCs and organic intermediates precedes the oxidation of CO to CO₂. The EPA thus feels that limiting CO emissions will insure low organic emissions and high DRE (Reference 1).

Oxygen measurements are required to correct CO concentrations to a common excess air rate indicated by excess oxygen in the flue gas. However, several studies have found that high excess air during combustion causes reduced DRE (References 32 and 17). Oxygen measurement by itself is not a good choice for a surrogate because many systems add air downstream from the combustion zone or use induced draft fans which can cause an influx of ambient air downstream of the furnace; however, in many systems it is useful for indicating excess air levels.

Total unburned hydrocarbon (TUHC) emissions should theoretically exceed emissions of POHCs and unoxidized organic compounds. Waterland (Reference 31) and Seeker et al. (Reference 29) found a nearly linear correlation of TUHC with DRE in pilot scale studies, while Trenholm and Oberacker (Reference 25) and Adams, Hartman and Wagoner (Reference 30) found no correlation in full scale incinerators and boilers. A major difficulty in using TUHC emissions is that the flame ionization detector responds far better to hydrocarbons than halocarbons (Reference 12). Thus apparent TUHC emissions will decrease with increased halocarbon content, which may lead to increased toxicity of the emissions.

2. Tracers

A technique which has received considerable attention is using an added tracer not normally found in the waste stream as a conservative indicator of waste DRE. Taylor (Reference 33) suggests that an ideal tracer should meet the following requirements:

1. It (and its decomposition products) should be relatively non toxic;
2. It should be more thermally stable than any other POHC present in the waste feed;
3. Technology should exist for accurate monitoring at both the inlet and exhaust to reliably determine tracer DRE on a near continuous basis;
4. Tracer DRE should exhibit a direct relationship with waste DRE.

Tsang and Shaub (Reference 34), Dellinger and Hall (Reference 12), and Mournighan (Reference 35) suggest three additional characteristics for a Tracer;

5. It should not be a product of incomplete combustion of the wastes or fuel;
6. It should not be found in typical waste streams;
7. It should be readily available at reasonable cost.

Tsang and Shaub (Reference 34) suggested that perfluorinated hydrocarbons such as CF_4 , C_2F_6 , C_3F_8 , C_4F_{10} , CF_3Cl , C_2F_5Cl , and SF_6 , might be suitable tracers. Freon 113 has been examined as a tracer by Mournighan (Reference 35), Wyss, Castaldini, and Mournighan (Reference 36), Chang and Sorbo (Reference 37), and Carnes (Reference 38). These studies found that Freon 113 could be used as a liquid surrogate and was as difficult to destroy as the POHCs used in the tests. Dellinger and Hall (Reference 39), however, found that monochlorobenzene was more thermally stable under pyrolytic conditions.

Sulfur hexafluoride (SF_6) has received considerable attention as a tracer and is specifically mentioned in the proposed rules as a candidate tracer needing further study (Reference 1). SF_6 is a gas which has been used in studies of atmospheric transport (References 40 and 41) studies of pollutant dispersal from smokestacks (References 42, 43, and 44), studies of air infiltration in mobile homes (Reference 45), mixing characteristics of gases in diesel engines (References 46), and mixing characteristics in natural gas flames (Reference 47). The characteristics that made SF_6 useful in these studies make it an attractive candidate tracer for hazardous waste work.

With respect to the first requirement for candidate tracers, SF₆ is non toxic (Reference 48), acting only as an asphyxiant. Decomposition products such as SOF₄, SO₂F₂, SOF₂ and HF are toxic, however the small amounts of SF₆ in the inlet would lead to very small amounts of these compounds in the exhaust, less than would be generated by fossil fuel combustion.

Theoretically, SF₆ should be more stable than organic wastes (References 4, 6, 33 and 34). Laboratory studies have shown it to be more difficult to destroy than toluene, benzene and trichloroethylene (References 6 and 49); carbon tetrachloride, tetrachloroethylene, 1,2,4-trichlorobenzene, and toluene (Reference 33); and 1,1,1 trichloroethane, carbon tetrachloride, and chloroform (Reference 50). Taylor (Reference 33) found that SF₆ was more stable than the wastes under both oxidative and pyrolytic conditions and that it was able to "track" the DRE of the wastes, i.e., SF DRE increased with increased waste DRE.

Studies of SF₆ in full-scale and pilot-scale systems have been very promising. England (Reference 51) and Mournighan (Reference 35) present the results of tests in a rotary cement kiln, a continuous asphalt plant, a batch asphalt plant, and a pilot scale circulating fluidized bed combustor. The research at the circulating bed combustor is also discussed in Chang and Sorbo (Reference 37). SF₆ DRE was lower than POHC DRE in all cases, and the DRE of the SF₆ successfully tracked the DRE of the POHCs. These studies also demonstrated that the technology exists to reliably introduce, sample and analyze SF₆ at commercial facilities.

SF₆ is easy to detect in concentrations on the order of parts per trillion using the electron capture detector of the gas chromatograph (GC/ECD) (References 34, 41, and 51). The high detector sensitivity and thermal stability of SF₆ would require only small amounts in the feed system. An advantage of the ECD is that it is insensitive to hydrocarbons. Instrumentation is available to provide near real-time analysis of SF (References 41 and 50).

With respect to the remaining requirements, SF₆ is rarely found in waste streams and is not a product of incomplete combustion (Reference 34), thereby eliminating the possibility of erroneous DRE measurements caused by tracer compounds in the waste stream. Finally, it is readily available at relatively low cost.

E. LITERATURE REVIEW OF RELATED STUDIES

This final section will briefly review some of the studies used by the EPA in developing the rules proposed for industrial boilers. The purpose is to identify systems and parameters that have been studied, emphasizing experimental methods and results applicable to boiler incineration of hazardous waste. Where appropriate, the results were discussed earlier in this chapter.

To develop the regulatory guidelines, the EPA sponsored full-scale and laboratory testing, including a three-phase study on the use of boilers for hazardous waste incineration. The first phase was concerned with addressing the feasibility of cofiring hazardous wastes with fuels in industrial boilers. The second phase was concerned with generating sampling and analysis protocols and locating candidate industrial boiler testing sites. Summaries of these early studies are given in Huffman, Wolbach and Waterland (Reference 20), Merrill et al. (Reference 52), and Castaldini et al. (Reference 53).

The third phase included pilot-and full-scale studies of waste incineration in boilers. The objective was to demonstrate the reliability of boilers for waste incineration and to identify parameters that affect waste DRE. Combustion by-products and added tracers were also studied to determine their feasibility for use as surrogates for POHC DRE. Many studies concerned with surrogate methods are not yet completed.

Castaldini, Unnasch and Mason (Reference 7), Castaldini et al. (Reference 54), and Castaldini et al. (Reference 28) discuss the results of field tests at eleven full scale industrial boilers. These tests looked at waterwall and firetube boilers using natural gas, fuel oil and pulverized coal as auxiliary fuels. The POHCs used were carbon tetrachloride, monochlorobenzene, trichloroethylene, and toluene. POHC DREs ranged from 99.90 to 99.99996 percent, with a mass weighted average of 99.998 percent.

These studies examined POHC DRE and organic emissions as a function of boiler type, waste type, and operating conditions. Although firetube boilers have smaller capacities, they were found to be as effective as watertube boilers. They found trends indicating that higher DREs were obtained under conditions of high waterwall heat release rate (high temperature profile throughout the furnace). No definitive correlation of CO with DRE was found, although DREs greater than 99.99 percent occurred under combustion conditions leading to CO emissions of less than 80 to 100 ppm.

Chehaske and Higgins (Reference 55) examined a hazardous waste mixture burned without auxiliary fuel in a small firetube boiler (92,000 Btu/hr, 358 square feet heat exchange surface). The mixture consisted of 98 percent toluene, with a balance of trichloroethylene, monochlorobenzene and carbon tetrachloride. All DREs were greater than 99.99 percent.

DeRosier et al. (Reference 26) conducted nonsteady firing tests in a 110,000 lb/hour (steam production) industrial boiler with both gas/waste and oil/waste cofiring. This was an extension of the work by Castaldini et al. (Reference 54) to unsteady and off-design operating conditions. The effects of varying load levels, excess air, and waste to fuel ratios were examined. The wastes used were carbon tetrachloride and monochlorobenzene. DREs for 106 of 112 runs were greater than 99.99 percent, averaging 99.998 percent. Similar DREs were obtained for both gas and oil

cofiring. CO concentrations ranged from 200 to 1000 ppm, however no correlation between DRE and CO emissions or other boiler operating conditions was observed.

Adams, Hartman and Wagoner (Reference 30) conducted steady state tests of two industrial boilers operating at 80 percent of design capacity (68,000 and 60,000 lb/hr steam production). Natural gas and fuel oil were used as fuels, with toluene, carbon tetrachloride, trichloroethylene, and monochlorobenzene as POHCs. The POHC feed constituted 16 percent of the fuel feed for the natural gas runs and 20 percent for the fuel oil runs. POHC DREs were greater than 99.997 percent. No correlation of POHC DRE with CO or TUHC emissions was observed.

Wolbach (Reference 27) and Wolbach and Garman (Reference 56) describe the results of pilot-scale testing cofiring chlorinated wastes with Number 2 distillate oil. The unit was designed to simulate a 40 million Btu/hr watertube boiler. DREs fell with decreased waterwall heat release rate and increased excess air. The authors suggest the drop in DRE resulted from the associated drop in furnace temperature. Excess air effects were nonlinear, with an optimum rate of 20 to 50 percent. In-flame destruction was found to account for only 90 to 99 percent of the DRE, the remaining destruction resulted from postflame oxidation and decomposition. The authors suggest that in-flame residence time is insufficient to destroy both POHCs and products of incomplete combustion, thus necessitating sufficient post flame time and temperature for complete waste destruction. No correlation could be drawn with respect to CO data as CO variation was minimal.

These studies have shown that properly operated industrial boilers are as effective as commercial incinerators at destroying most wastes. However, in view of the risks posed by improper operation, the EPA has decided to regulate boilers burning hazardous wastes as commercial incinerators (Reference 1). These rules are scheduled to be approved and promulgated in June, 1988.

SECTION III

EXPERIMENTAL APPROACH

To accomplish the objectives stated in Chapter I a pilot-scale incineration tunnel designed to simulate a 100-horsepower firetube boiler was constructed. Also assembled was a gas sampling and analysis system consisting of continuous emission monitors and a gas chromatograph. The control over experimental parameters afforded by a laboratory environment was expected to eliminate many of the problems associated with conducting studies in a full-scale operational unit. Descriptions of both the tunnel facility and gas analysis system, along with the experimental procedure, are presented in this chapter.

A. Incineration Tunnel Facility

The incineration tunnel is designed to simulate a 100-horsepower firetube boiler similar to smaller industrial boilers used for liquid waste incineration. It can be fired on either liquid fuels or natural gas. The major subsystems are the tunnel, fuel feed, liquid waste feed, burner and blower. The tunnel facility is shown schematically in Figure 1.

1. Incineration Tunnel

The incineration tunnel is mounted horizontally and consists of four water-cooled ductile iron sections. Overall length is three meters, with an internal diameter of 0.5 meters. The first section is 1 meter long and lined with an eight 8-centimeter thick refractory. The remaining sections are each 2/3 of a meter long and are not refractory-lined.

Each section is surrounded by a galvanized iron water jacket. Shutoff valves allow water flow to each section to be independently controlled. Water flow is maintained by a circulation pump and cooled through a roof-mounted radiator.

2. Burner and Blower

The burner is a type ARC Model 550 combination gas and oil burner manufactured by Ray Burner, Co. Maximum rated output is 125 water horsepower. Liquid atomization is accomplished by a rotating air-blast atomizer. Primary air used for atomization accounts for approximately 20 percent of the combustion air and

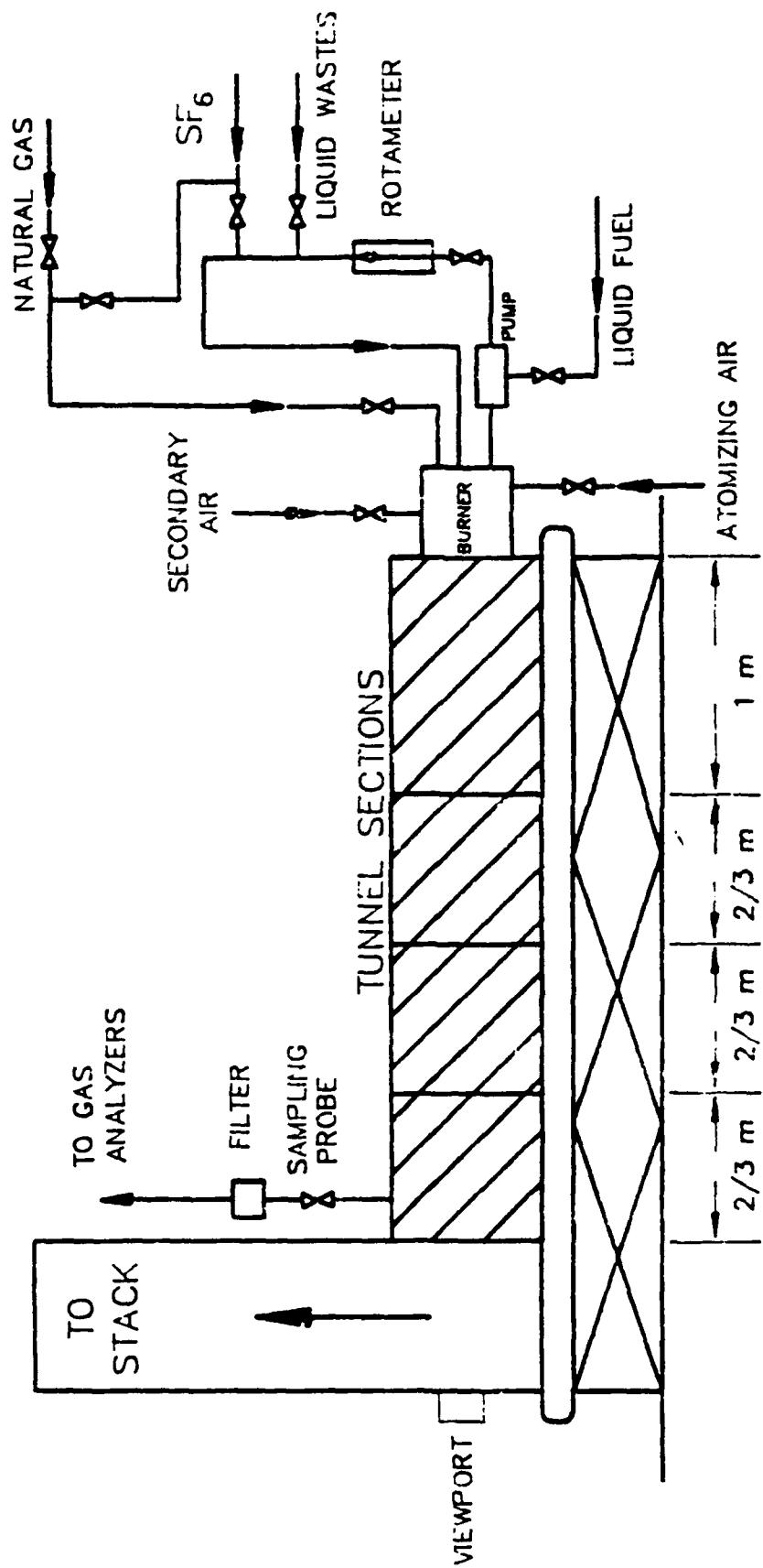


Figure 1. Schematic of Incineration Tunnel.

is supplied by an internal fan. Secondary air is supplied by an external Aerovent model 4140 blower and forced through a swirl plate to improve fuel-air mixing in the tunnel.

The static pressure in the air supply duct was measured with a water manometer which had been previously calibrated for air flow rate in this system. The manometer was calibrated using volume flow rates obtained from velometer readings in both the air inlet duct and in the stack. The inlet air flow was also calculated using data obtained from the continuous emission monitors with the tunnel fired on natural gas. Both methods gave air flow rates within 20 percent of each other. For later uncertainty analysis air flow measurements were taken to be accurate within 20 percent.

3. Fuel, Waste and Sulfur Hexafluoride Feed Systems

Figure 2 is a schematic of the fuel, waste, and SF₆ feed systems. The flow rates of the liquid fuel, surrogate wastes, and SF₆ were measured using previously calibrated rotameters. Calibration curves were developed for each rotameter and flow measurements were taken to be accurate within 10 percent. The system was designed to simultaneously and independently inject up to four wastes at a time. The natural gas flow rate was measured by the utility supply meter.

Liquid fuel was stored in 55-gallon drums and pumped to the burner by a pump mounted on the burner. The fuel rotameter was located between the pump and the burner. The wastes were forced from their containers by an upstream compressor and injected into the fuel line downstream of the fuel rotameter. All surrogate wastes were laboratory-grade, purchased new.

The liquid fuel was an isoparaffin solvent marketed by Phillips Petroleum Company as Soltrol® 100. The isoparaffin was used instead of a fuel oil to avoid analytical background errors caused by fuel oil combustion products or by trace amounts of the wastes present in the fuel oil. Using the isoparaffin as the fuel also permitted an exact knowledge of the fuel stream composition.

Gaseous SF₆, 99.7 percent pure, was supplied from a pressurized cylinder at approximately 300 psi and reduced to 40 psi at the cylinder regulator. Flow rates were measured using a rotameter prior to injection into the fuel line near the waste injection point. A second line allowed SF₆ injection into the natural gas line.

B. EXHAUST GAS ANALYSIS

1. Gas-Sampling-System

The gas-sampling system consisted of a water-cooled sampling rake, a heated sampling line, and a continuously operating heated pump. The sampling system was heated to approximately 200°C to prevent hydrocarbon condensation. The

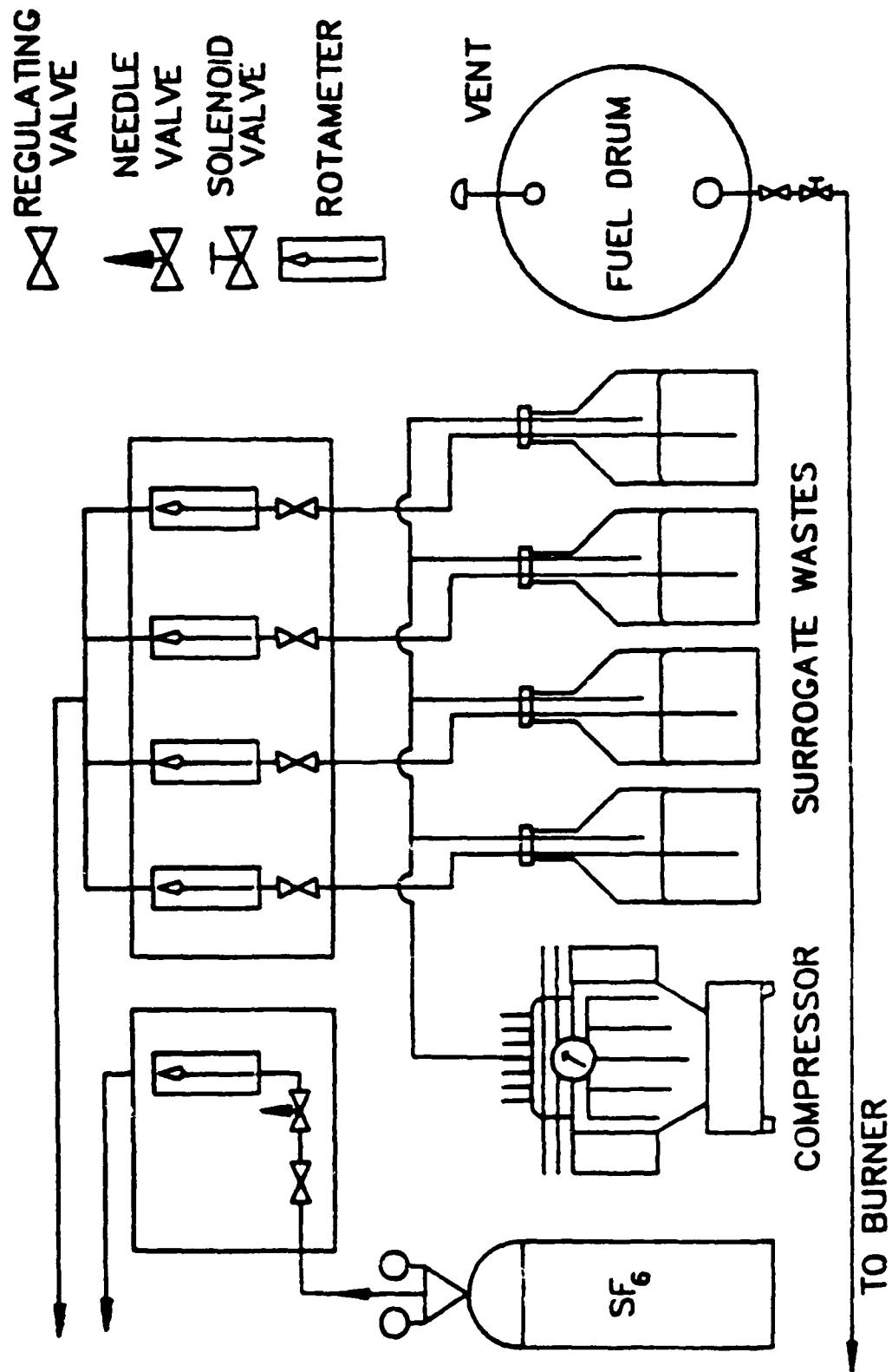


Figure 2. Schematic of Fuel, Waste and SF₆ Feed Systems.

entire system was carefully checked for leaks to prevent sample dilution. Catalytic reactions caused by sample line interaction were not expected to significantly affect concentrations of the species of interest.

Gas samples were withdrawn through a sample rake located near the end of the final tunnel section. The sample rake was constructed of 1.25-centimeter high-temperature stainless steel tubing. A 2.54 centimeter diameter stainless steel tube served as a water jacket. The exhaust gases at this part of the tunnel were assumed to be homogenous due to the turbulence in the tunnel. However, to obtain a representative sample of the exhaust gases, five holes drilled in the rake were located to provide concentric equal area sampling throughout the tunnel cross-section.

The heated sample line was made of 0.6-centimeter stainless steel tubing and was used for sample transport to the gas analyzers located in a nearby control and analysis room. A 2-micrometer filter was located between the sample rake and the sample line. The gas sampling pump was a KNF Neuberger model N 010 ST.11I capable of delivering nine liters per minute. It was heated and maintained at a constant temperature of 200°C.

2. Continuous-Emission-Monitors

Figure 3 is a schematic of the gas analysis system. The continuous emission monitors (CEMs) used were a Bendix model 402 hydrocarbon analyzer, a Bendix model 864 carbon dioxide analyzer, and a Teledyne model 990 CO/O₂ portable flue gas analyzer. A Perkin-Elmer model Sigma 300 gas chromatograph with both flame ionization and electron capture detectors was used for measuring waste and SF₆ exhaust concentrations.

Samples destined for the gas chromatograph and the hydrocarbon analyzer were kept heated to eliminate hydrocarbon sample loss through condensation. Thus, water vapor present in the sample was not removed and the data for these two instruments is recorded as concentration on a wet basis.

Operating conditions for the remaining continuous emission monitors required that water vapor in the gas sample be removed and that the sample temperature be lowered to near ambient. An ice-bath condenser was used to both condense the water vapor and reduce the temperature. Gas concentrations from these instruments are thus reported on a dry basis.

The hydrocarbon analyzer had its own sample pump and worked best when drawing samples from the low pressure side of the main sample line. Sample gas was supplied to the remaining instruments by the main sample pump, which ran continuously to maintain current samples at the instruments.

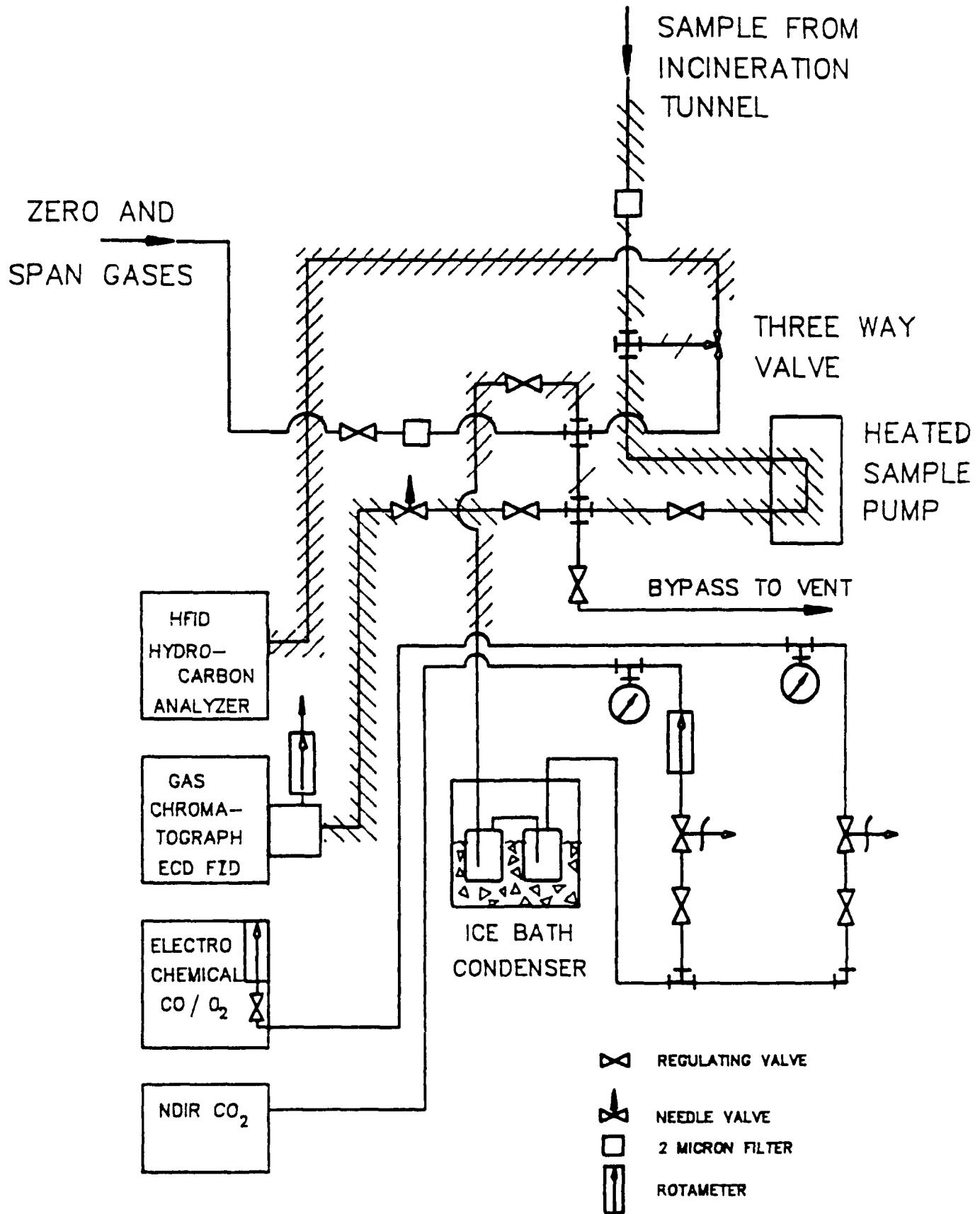


Figure 3. Schematic of Gas Analysis System.

Calibration gases for each analyzer were supplied from gas cylinders. Flow meters and pressure gages associated with each instrument were used to insure calibration and sampling at the same pressure and flow rate. Flow control of the sample and calibration gases was accomplished through the use of manual throttle and shutoff valves located near the instruments and solenoid valves located near the gas cylinders. Nitrogen was used as the zero gas.

3. Gas-Chromatograph

The gas chromatograph (GC) was modified to permit automatic switching between the flame ionization detector (FID) and the electron capture detector (ECD). Three automatic sampling valves were used to direct the sample onto to the desired column, and for column backflushing. The FID was used for quantitative analysis of the surrogate wastes present in the sample and the ECD was used for quantifying SF₆ in the exhaust. A Perkin Elmer LCI-100 integrator was used for data integration, detector selection, and valve switching.

Column Set 1 was used for SF₆ separation and was externally mounted for operation at ambient temperature. It consisted of a 6-inch by 1/8-inch 5 percent H₃PO₄ on 60/80 G(AW) column, followed by a 12-inch by 1/8-inch 5A molecular sieve 45/60 mesh conditioned for 1 hour at 300°C as a stripper column, followed by a 16-foot by 1/8-inch 5A molecular sieve 45/60 mesh conditioned for 1 hour at 300°C. This set was connected to a 10 port automatic sampling valve for backflushing to vent or forward feeding to the ECD. Sample loop size was 1 cc. Nitrogen was used as the carrier gas, with flow rates of 26 cc/min through the column and 41 cc/min makeup.

Column 2 was installed in the GC oven and was used for hydrocarbon separation. It was a Supelco[®] 30 meter SPB-1 with 0.75 mm inner diameter, 1-micrometer film thickness. Flow through this column was controlled by six- and four-port automatic sampling valves. The six-port valve was used for sample injection onto the column and the four-port valve was used to control flow direction through the column. The four-port valve was used to backflush the column after each run. Sample loop size was 1/4 cc. Helium was used as the carrier gas and for column backflushing, with a flow rate of four cc/min through the column.

The ten-and six-port valves were externally mounted on the GC in a heated valve enclosure, maintained at 175°C by an instrument temperature controller. The four-port valve was mounted in the GC oven. Automatic valve switching was controlled by timed event relays incorporated in the method used by the LCI-100 integrator. The GC oven temperature was maintained at 120°C, with a detector temperature of 250°C. Peak files from the integrator were stored on a MODCOMP Classic 32/85 computer manufactured by Modular Computer Systems.

C. EXPERIMENTAL PROCEDURES

1. Incineration Tunnel: Liquid Wastes and Sulfur Hexafluoride

Five liquid chemicals typical of Air Force waste solvents were burned in the incineration tunnel. The chemicals were methyl ethyl ketone, toluene, isopropanol, trichloroethylene, and monochlorobenzene. The wastes were cofired with the isoparaffin, Soltrol® 100, as the liquid fuel. SF₆ was injected into the fuel line.

The tunnel was first heated on natural gas, then switched to the Soltrol® 100. Cooling water was circulated through the first two tunnel sections. The Soltrol® 100 was first burned over a wide range of fuel and air flows to establish background hydrocarbon concentrations. Both the gas chromatograph and the hydrocarbon analyzer indicated no hydrocarbons present, thereby eliminating fuel combustion as a source of background errors within the limits of detection of these instruments.

Only one waste was burned during each run to maximize experimental control and to minimize background errors. Some difficulty was encountered in detecting toluene, methyl ethyl ketone, and isopropanol in the exhaust when these wastes were burned. The detection limit for these chemicals on the GC/FID was 0.4 parts per million. Even when burned without auxiliary fuel they could not be detected under any flow combination of waste and air. Destruction removal efficiencies for these wastes are therefore based on detection limits and are reported for only one run each.

The experiment was then focused on the more difficult to destroy and more easily detected chlorinated hydrocarbons, trichloroethylene and monochlorobenzene. Even these could only be detected under conditions of high air flow (later determined to be between 65 and 225 percent).

During the experiment, the thermocouple used for recording temperature in the hot zone burned out; as a result, no temperature data were recorded. Temperature is an important parameter affecting DRE, but it was not the major focus of this research project, therefore temperature data loss was not considered critical.

The run conditions are reported in Table 1. The run numbers are simply used for keeping track of the data for later presentation and do not indicate the order in which the data were collected.

TABLE 1. RUN CONDITIONS FOR THE LIQUID WASTE BURNS IN THE INCINERATION TUNNEL.

Run #	Waste	Waste Flow mL/min	Fuel Flow mL/min	AirFlow cubic meters/min
1, 2	Trichloroethylene	63	404	8.3
3	Trichloroethylene	118	404	8.3
4	Trichloroethylene	63	448	8.3
5	Trichloroethylene	118	448	8.3
6	Trichloroethylene	63	315	8.3
7-10	Trichloroethylene	63	242	8.3
11, 12	Trichloroethylene	23	242	8.3
13	Monochlorobenzene	131	205	7.4
14	Monochlorobenzene	131	242	8.3
15	Monochlorobenzene	77	316	8.3
16	Monochlorobenzene	77	389	8.3
17	Monochlorobenzene	77	205	8.3
18	Monochlorobenzene	77	242	7.4
19	Monochlorobenzene	77	315	7.4
20	Monochlorobenzene	131	242	7.4
21	Toluene	435	0	7.4
22	Isopropanol	441	0	6.5
23	Methyl Ethyl Ketone	655	0	6.5

SF₆ was injected into the fuel line at 8.9 mL/min (0.054 mg/min) for the trichloroethylene runs and 5.8 mL/min (0.035 mg/min) for the other runs.

The tunnel was allowed to run at the new conditions for at least 15 minutes before data from the gas analysis instruments were recorded. Each instrument was zeroed and spanned before the experiment and after every fourth run. Carbon monoxide concentrations exceeded the upper detection limit of 1000 ppm for the CO monitor during runs 3, 6-14, 17, 18, and 20. GC and CEM data are reported with the reduced data in Chapter IV on analysis and results.

2. Incineration Tunnel: Natural Gas and Sulfur Hexafluoride

During this part of the experiment, the tunnel was fired on natural gas with SF₆ added to the gas line at 5.8 mL/min (0.035 mg/min). Fuel flow rates of 0.10, 0.20, and 0.26 kg/min and air flow rates of 7, 8, 9, 10, and 13 kg/min were used. The fuel flow was varied only after the full range of air flows had been exhausted. A GC background check on the gas supply confirmed vendor information that the gas was greater than 98 percent methane. As before, data were recorded from the continuous

emission monitors and the GC/ECD. Each instrument was zeroed and spanned before beginning and after every fifth run. Data from this part of the experiment is presented in Chapter IV on analysis and results.

3. Steam Plant Boiler: Natural Gas and Sulfur Hexafluoride

The final phase of the experiment was conducted at the University of Florida steam plant, Boiler 5. The unit is rated at 80,000 lb/hour steam production. Natural gas was used as the fuel.

SF₆ was metered into the gas line, using the same system used for the incineration tunnel study. As in the incineration tunnel studies, stack samples were continuously withdrawn, using the heated sample pump. GC analysis of SF was conducted in the same manner as was done in the incineration tunnel.

Three fuel flow rates were used. Data were obtained while running the unit at various air flow rates for a given fuel flow rate, generating 25 data points. These flow rates are presented in Chapter IV with the reduced data.

SECTION IV

ANALYSIS AND RESULTS

In analyzing the data, emphasis was placed on relating waste destruction removal efficiency (DRE) to data obtained from the continuous emission monitors (CEMs) and to the DRE of SF₆. The CEM data were also compared to SF₆ DRE in the incineration tunnel operating in both liquid and gas fired modes. The relationship of excess air with waste DRE and SF₆ DRE was also examined. The work at the steam plant generated information on the effects of excess air on SF₆ DRE in a natural gas-fired industrial boiler.

A. Incineration Tunnel: Liquid Wastes and Sulfur Hexafluoride

1. Data Analysis

The experimental data were analyzed using a Lotus spreadsheet which is included in the Appendix. To determine the DRE of the wastes and the sulfur hexafluoride it was necessary to determine the total exhaust flow. The exhaust flow rate was determined by conducting a chemical balance on the inlet fuel, waste, and air flows, assuming complete combustion. Stack gas flow rates were not directly measured for several reasons. The high turbulence in the stack made isokinetic sampling very difficult. Also, using Federal Register methods for flow measurement would have slowed data collection. Furthermore, the accurate characterization and measurement of the feeds available during the incineration tunnel experiments allowed determination of the stack gas flow rate by species balance.

For stack gas flow calculations, concentrations of dissociation products and incomplete combustion products were assumed to be orders of magnitude less than the major exhaust gas components. At the excess air flows of this experiment the stack gases are largely dominated by air. Furthermore, the excess air limits temperature and the corresponding dissociation products of N₂, O₂, and H₂O. This assumption was supported by the data. For example, highest concentrations of TUHC ranged up to 2000 ppm during some runs (on the order of 0.2 percent). Therefore, determining the exhaust flow rate by chemical balance of the reactants is assumed to be accurate within the uncertainties of the measuring instruments.

The analysis consisted of solving the chemical equation of the form



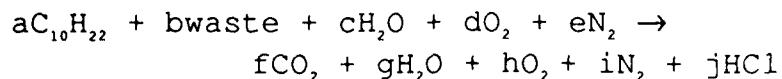
HCl concentrations were found to be small compared to the major exhaust gas components, but were included for later analysis of HCl emission rates. Water vapor in the inlet air was determined from ambient temperature and relative humidity using psychrometrics.

The Soltrol® 100 consisted of an isoparaffin mixture with molecular composition $C_{10}H_{22}$. Table 2 contains the physical constants for the fuel, surrogate wastes, and sulfur hexafluoride used in the data analysis.

TABLE 2. PHYSICAL CONSTANTS FOR THE WASTES, FUEL, AND SULFUR HEXAFLUORIDE USED IN THE DATA ANALYSIS.

Chemical	Molecular Weight	Density g/mL
Trichloroethylene $CHClCCl_2$	131.39	1.446
Monochlorobenzene C_6H_5Cl	122.56	1.101
Toluene $C_6H_5CH_3$	92.14	0.8687
Isopropanol $[CH_3]_2CHOH$	60.10	0.7850
Methyl Ethyl Ketone $CH_3COC_2H_5$	72.11	0.8040
Soltrol® 100 $C_{10}H_{22}$	141.59	0.7440
Sulfur Hexafluoride SF_6 (gaseous)	146.05	0.0061

For the liquid runs the chemical equation becomes



The variables a, b, c, d, and e are known from the inlet flow rates of fuel, waste, and air. The variables f, g, h, i, and j are determined from a species balance for chlorine, carbon, hydrogen, oxygen, and nitrogen. For example, for monochlorobenzene

$$\begin{aligned}
 j &= b \\
 f &= 6b + 10a \\
 2g &= 22a + 5b + 2c - j \\
 2h &= 2d + c - 2f - g \\
 i &= e
 \end{aligned}$$

The total molar exhaust flow is given by $f+g+h+i+j$. Similar equations were developed for each of the five wastes.

The DRE was determined from

$$DRE = 1 - m(\text{in})/m(\text{out}) \quad (1)$$

where m = mass flow the compound.

The mass exhaust flow rate of the chemical of interest was found by using the GC data and the calculated total exhaust flow rate. The input mass flow rate was determined from the input volumetric flow and the density of the compound.

$$m(\text{out}) = GC * EF * M \quad (2)$$

$$m(\text{in}) = Q * \rho \quad (3)$$

where

GC = chemical concentration in the exhaust measured by the gas chromatograph

EF = molar exhaust flow rate

M = molecular weight of the compound

Q = input volume flow rate

ρ = density of the compound at the inlet.

2. Results

The reduced data for the liquid waste runs are presented in Tables 3 and 4. Toluene, isopropanol, and methyl ethyl ketone were burned without auxiliary fuel and were not detected in the exhaust by the GC/FID or the hydrocarbon analyzer under any run conditions. The DREs were calculated, based on a detection limit of 0.4 ppm for the GC/FID. The DREs for these three chemicals were determined to be at least 0.99997.

SF₆ DREs for these runs were much lower at 0.9790 for the toluene run and 0.9238 for the isopropanol run. Data for SF₆ cofired with methyl ethyl ketone were not obtained, although the results are expected to be similar to those obtained for the other nonchlorinated chemicals.

TABLE 3. REDUCED DATA AND DATA FROM THE GAS CHROMATOGRAPH FOR SF6 AND LIQUID WASTES BURNED IN THE INCINERATION TUNNEL.

RUN #	WASTE	WASTE FLOW g/min	FUEL FLOW g/min	AIR FLOW kg/min	SF6 FLOW mg/min	WASTE IN EXHAUST ppm from GC	SF6 IN EXHAUST ppb from GC	WASTE DRE	SF6 DRE
1	TRICHLOR	85	300	9	54	2.2	567	0.9990	0.4978
2	TRICHLOR	85	300	9	54	1.5	593	0.9993	0.4749
3	TRICHLOR	160	300	9	54	4.3	590	0.9989	0.4775
4	TRICHLOR	85	335	9	54	0.4	527	0.9998	0.5313
5	TRICHLOR	160	335	9	54	1.1	851	0.9997	0.2437
6	TRICHLOR	85	235	9	54	20.0	717	0.9905	0.3706
7	TRICHLOR	85	180	9	54	1.3	721	0.9994	0.3705
8	TRICHLOR	85	180	9	54	135.7	772	0.9363	0.3260
9	TRICHLOR	85	180	9	54	214.6	753	0.8993	0.3433
10	TRICHLOR	85	180	9	54	198.7	853	0.9068	0.2560
11	TRICHLOR	30	180	9	54	60.7	873	0.9214	0.2386
12	TRICHLOR	30	180	9	54	77.6	793	0.8995	0.3083
13	MCB	145	150	8	35	124.4	623	0.9692	0.2480
14	MCB	145	180	9	35	198.1	633	0.9452	0.1463
15	MCB	85	235	9	35	17.5	549	0.9918	0.2575
16	MCB	85	290	9	35	0.5	226	0.9998	0.6921
17	MCB	85	150	9	35	223.2	685	0.8963	0.0819
18	MCB	85	180	8	35	52.7	719	0.9779	0.1317
19	MCB	85	235	8	35	4.0	587	0.9983	0.2861
20	MCB	145	180	8	35	2.0	629	0.9995	0.2375
21	TOLUENE	380	---	8	35	ND	18	>0.99997	0.9790
22	ISOPROPANOL	345	---	7	35	ND	72	>0.99998	0.9238
23	MEK	525	---	7	---	ND	---	>0.99998	---

TABLE 4. REDUCED DATA AND DATA FROM CONTINUOUS EMISSION MONITORS FOR SF6 AND LIQUID WASTES BURNED IN THE INCINERATION TUNNEL.

RUN #	WASTE	CO2		CO		UHC ppm	EQUI- VALENCE RATIO	EXCESS AIR %	SF6 CONCENTRATION mg sf6/kg fuel+wastet+air	WASTE IN FUEL STREAM mass %
		%	ppm	%	ppm					
1	TRICHLOR	5.5	12.5	666	11	0.53	90	5.8	5.8	22
2	TRICHLOR	6.4	11.8	420	4	0.53	90	5.8	5.8	22
3	TRICHLOR	6.5	11.6	985	16	0.54	85	5.7	5.7	35
4	TRICHLOR	7.6	10.9	275	1	0.58	70	5.7	5.7	20
5	TRICHLOR	8.2	10.7	645	6	0.60	65	5.7	5.7	32
6	TRICHLOR	5.5	14.3	>1000	200	0.42	140	5.8	5.8	26
7	TRICHLOR	4.0	15.7	>1000	1500	0.32	210	5.8	5.8	32
8	TRICHLOR	4.0	15.7	>1000	1500	0.32	210	5.8	5.8	32
9	TRICHLOR	3.9	15.8	>1000	1500	0.32	210	5.8	5.8	32
10	TRICHLOR	3.8	16.0	>1000	1500	0.32	210	5.8	5.8	32
11	TRICHLOR	3.7	16.3	>1000	1800	0.31	225	5.9	5.9	15
12	TRICHLOR	3.6	16.3	>1000	1805	0.31	225	5.9	5.9	15
13	MCB	5.0	14.4	>1000	ND	0.43	130	3.5	3.5	48
14	MCB	4.8	14.6	>1000	700	0.43	130	3.8	3.8	38
15	MCB	5.6	13.7	960	150	0.47	115	3.8	3.8	27
16	MCB	7.0	11.7	210	14	0.56	80	3.8	3.8	27
17	MCB	4.0	15.9	>1000	1400	0.33	200	3.8	3.8	27
18	MCB	5.0	14.4	>1000	500	0.42	140	4.2	4.2	36
19	MCB	5.9	13.3	704	70	0.52	90	4.2	4.2	36
20	MCB	5.3	13.9	>1000	200	0.48	110	4.2	4.2	48
21	TOLUENE	9.0	10.4	27	4	0.63	60	3.9	3.9	100
22	ISOPROPANOL	6.2	13.1	22	1	0.50	100	4.7	4.7	100
23	MEK	7.0	11.2	46	ND	0.78	30	—	—	100

The trichloroethylene and the monochlorobenzene did not burn well without the use of the auxiliary fuel. This was evidenced by poor flame conditions and difficulty in maintaining a stable flame. These two wastes and SF₆ were successfully detected in the exhaust for a variety of run conditions. These chemicals are known to be more difficult to destroy than the nonchlorinated hydrocarbons. Further discussion of the data from the incineration tunnel focuses on the runs with these compounds, from which the majority of the data were collected.

The incineration tunnel allowed data collection over a wide range of run conditions. While conducting the experiment, run conditions were adjusted to provide good data resolution on the gas chromatograph, with an emphasis on gathering as much data as possible, rather than obtaining "four-nines" destruction of the wastes. Trichloroethylene and monochlorobenzene DREs ranged from 0.8963 to 0.9998. Sulfur hexafluoride DREs were much lower, ranging from 0.0819 to 0.6921 for these runs. Much higher destruction levels were possible, but it was considered more important to maintain exhaust concentrations above the GC detection limit.

Figures 4 and 5 compare the DRE of SF₆ with the DRE of trichloroethylene and monochlorobenzene. In all cases the SF₆ DRE was significantly lower than the waste DRE. The SF₆ DRE also tracked the DRE for the wastes during most runs. Error analysis on the trichloroethylene and SF₆ data indicated an uncertainty of the breakthrough emissions of less than 25 percent. Uncertainty of the other data is expected to be in the same range.

Figure 6 shows the DREs of trichloroethylene and sulfur hexafluoride for Runs 1 through 12 plotted against the CO₂ exhaust concentration as indicated by the continuous emission monitor. CO₂ concentrations are reported on a dry basis. Separate axes are used to permit maximum spread of the data. Figure 7 is a similar plot for monochlorobenzene and sulfur hexafluoride DRE for runs 13 through 20.

An increase in CO₂ concentration corresponds to an increase in DRE for the wastes. This is not unexpected as CO₂ is a major product of hydrocarbon combustion and the generation of CO₂ is a direct result of waste oxidation. This trend is also observed for SF₆ during the trichloroethylene runs, although there is much more scatter in the data. No relationship between SF₆ DRE and CO emissions was observed during the monochlorobenzene runs.

Figures 8 and 9 are similar plots of the DREs versus O₂ exhaust concentration as indicated by the continuous emission monitor (dry basis). For both the wastes and SF₆, DRE decreases as exhaust oxygen concentration increases. The pattern is especially evident for the wastes with exhaust O₂ concentrations above 14 percent.

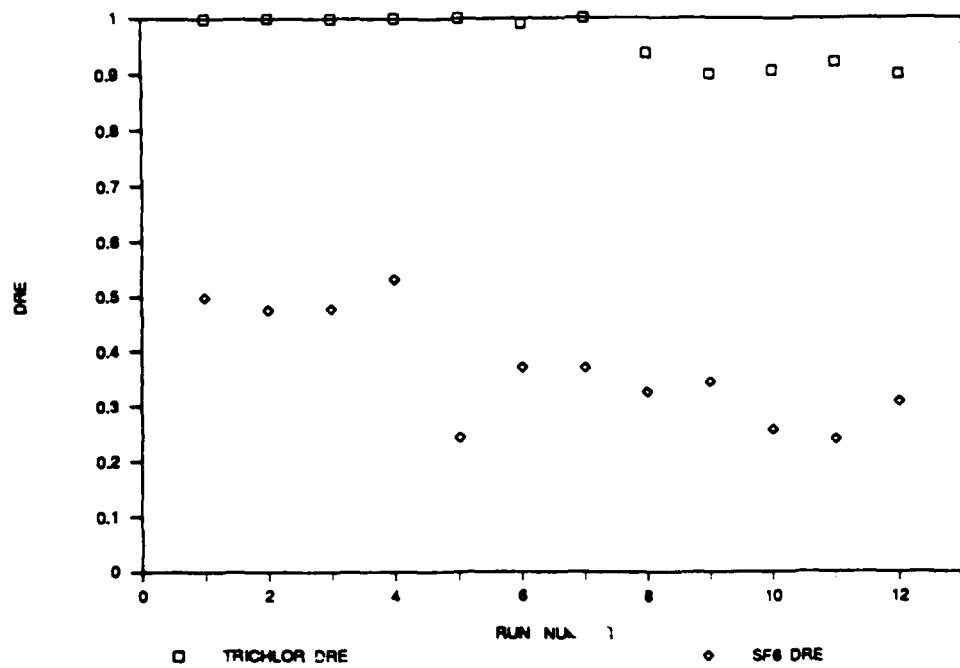


Figure 4. Comparison of Trichloroethylene and Sulfur Hexafluoride DRE for Liquid Fuel Firing in the Incineration Tunnel.

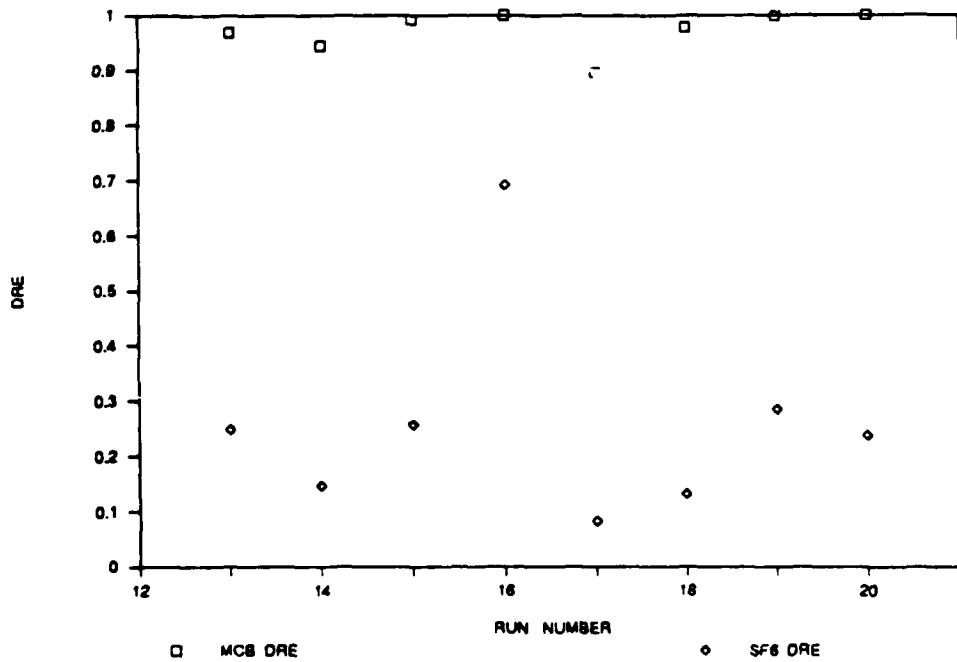


Figure 5. Comparison of Monochlorobenzene and Sulfur Hexafluoride DRE for Liquid Fuel Firing in the Incineration Tunnel.

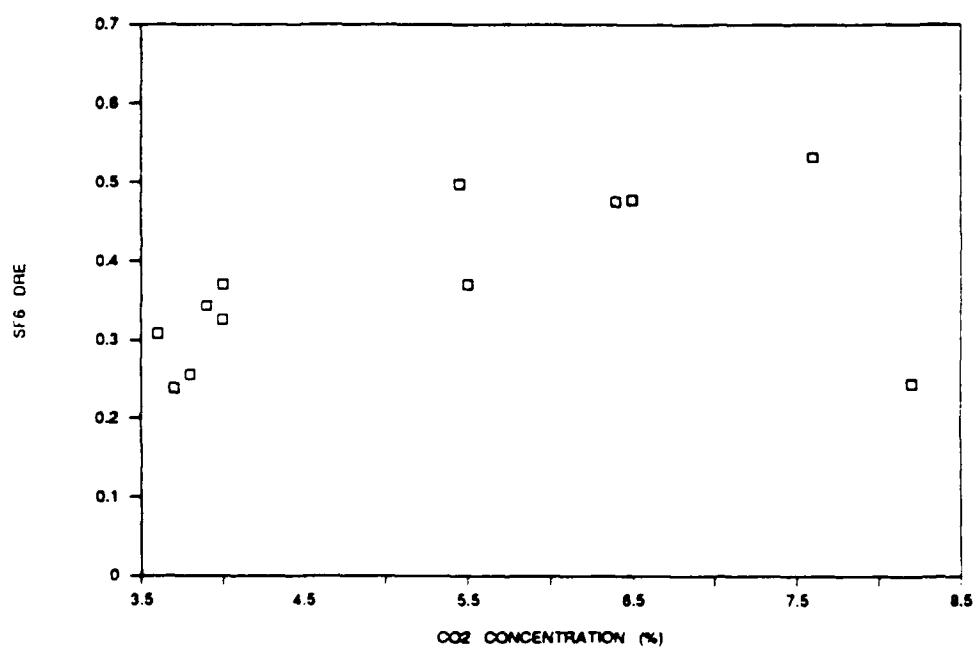
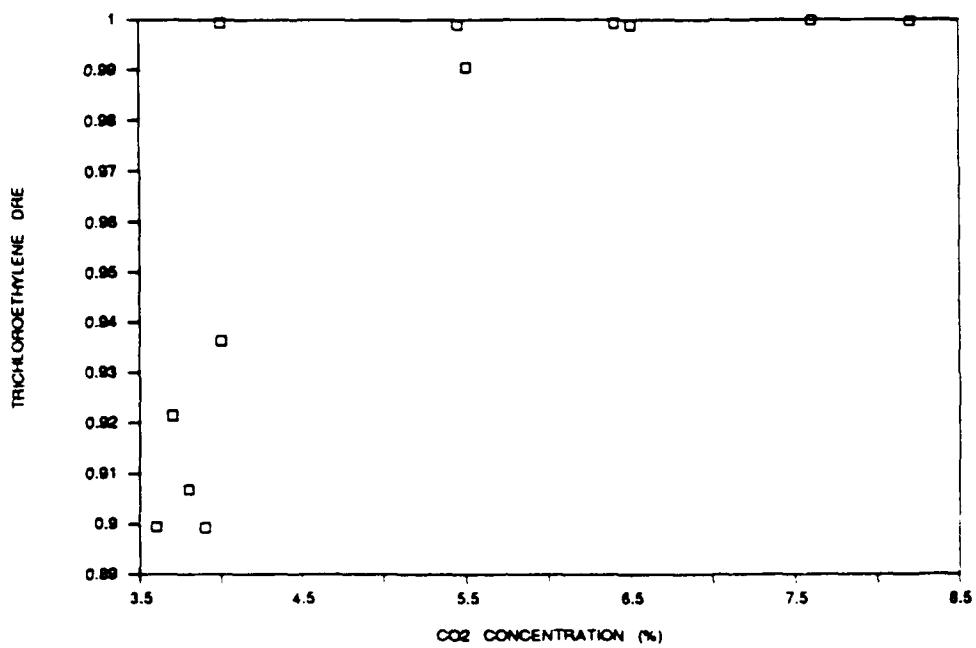


Figure 6. Trichloroethylene and Sulfur Hexafluoride DRE versus Exhaust CO₂ Concentration for Liquid Fuel Firing in the Incineration Tunnel.

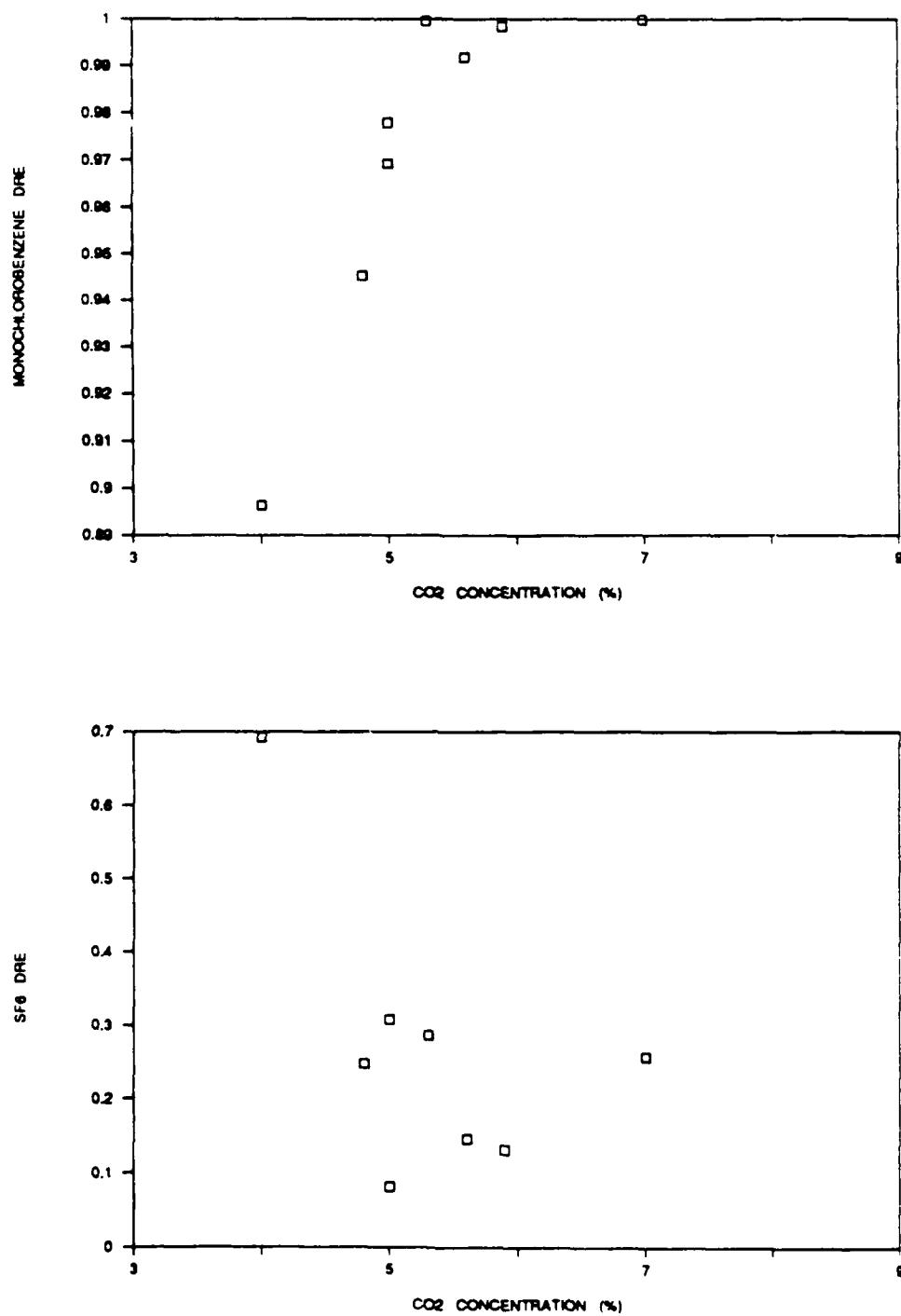


Figure 7. Monochlorobenzene and Sulfur Hexafluoride DRE versus Exhaust CO₂ Concentration for Liquid Fuel Firing in the Incineration Tunnel.

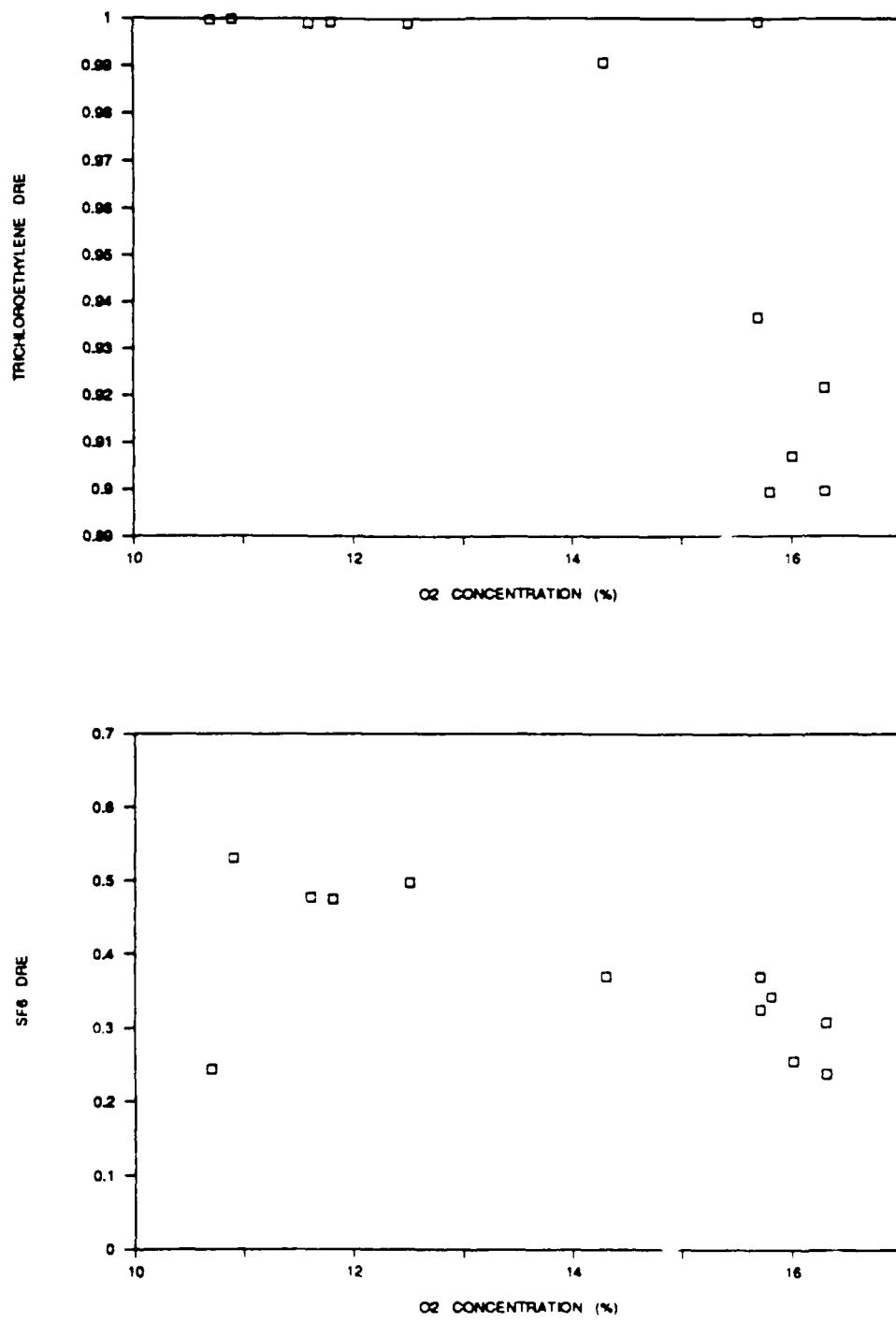


Figure 8. Trichloroethylene and Sulfur Hexafluoride DRE versus Exhaust O₂ Concentration for Liquid Fuel Firing in the Incineration Tunnel.

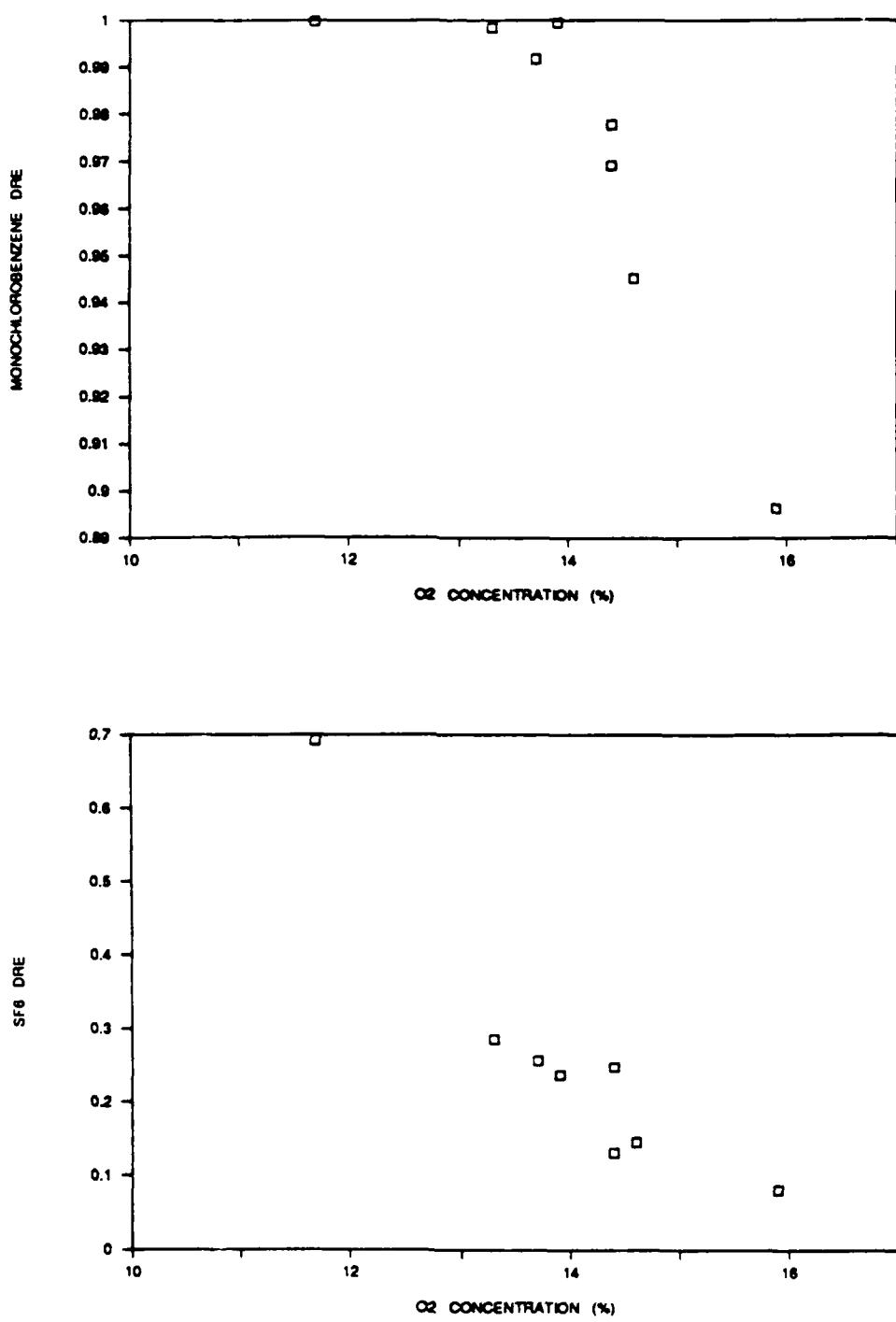


Figure 9. Monochlorobenzene and Sulfur Hexafluoride DRE versus Exhaust O₂ Concentration for Liquid Fuel Firing in the Incineration Tunnel.

Figures 10 and 11 show the DREs plotted against the excess air. These figures are essentially the same as Figures 8 and 9 for exhaust O₂ concentration. For the wastes, a sharp drop in DRE is observed for excess air above 100-120 percent. SF₆ DRE also decreases with increased excess air.

From the data collected during this experiment, it is not possible to pinpoint the cause of the drop in DRE with increased excess air. Air flow affects both the chemical kinetics and fluid mechanics in the tunnel. Reduced DRE may have resulted from slowed chemical reaction rates caused by thermal quenching by the excess air. The increased air flow may also have adversely affected the turbulent mixing in the tunnel, resulting in reduced destruction. It is also possible that the drop in DRE was partly caused by reduced atomization efficiency at the reduced liquid flow rates. While commercial boilers do not normally operate at the high excess air rates used in this experiment, the detrimental effects of large amounts of unnecessary air, is illustrated.

Figures 12 and 13 are similar plots of the DREs versus exhaust hydrocarbon concentration measured by the hydrocarbon analyzer. Water vapor was not removed from the sample prior to analysis and concentrations are reported on a wet basis. For both the wastes and SF₆, increased exhaust hydrocarbon concentration is indicative of lower DRE, although there is some scatter in the trichloroethylene data.

Exhaust hydrocarbons may be either unburned fuel or waste, or products of incomplete combustion of the fuel or waste. The earlier background check indicated no hydrocarbons present in the exhaust when burning unspiked fuel. Therefore, the hydrocarbons measured during the waste burns are most likely unburned waste or products of incomplete combustion. The possibility also exists that fuel combustion was not as efficient when the fuel was cofired with the wastes. In any case, exhaust hydrocarbons are directly indicative of incomplete combustion, either of the fuel or the waste, or both.

Figures 14 and 15 show the DREs of the wastes and SF₆ plotted against the exhaust CO concentration (dry basis). As discussed in Section III many of the CO measurements were above the detection limit of the CO analyzer. Only those values within the range of the analyzer are plotted. A trend of lower DREs with increased CO concentration is evident, although too few data points are plotted to draw definite conclusions. The high DREs for toluene, methyl ethyl ketone and isopropanol were accompanied by relatively low CO (22-46 ppm) and unburned hydrocarbon concentrations (0-4 ppm).

The concentration of SF₆ in the incinerator inlet is given in Table 4. These data should prove useful in the development of a standard method for using SF₆ as a tracer. The concentrations ranged from 3.75 to 5.83 milligrams of SF₆ per kilogram of total input (fuel + waste + air).

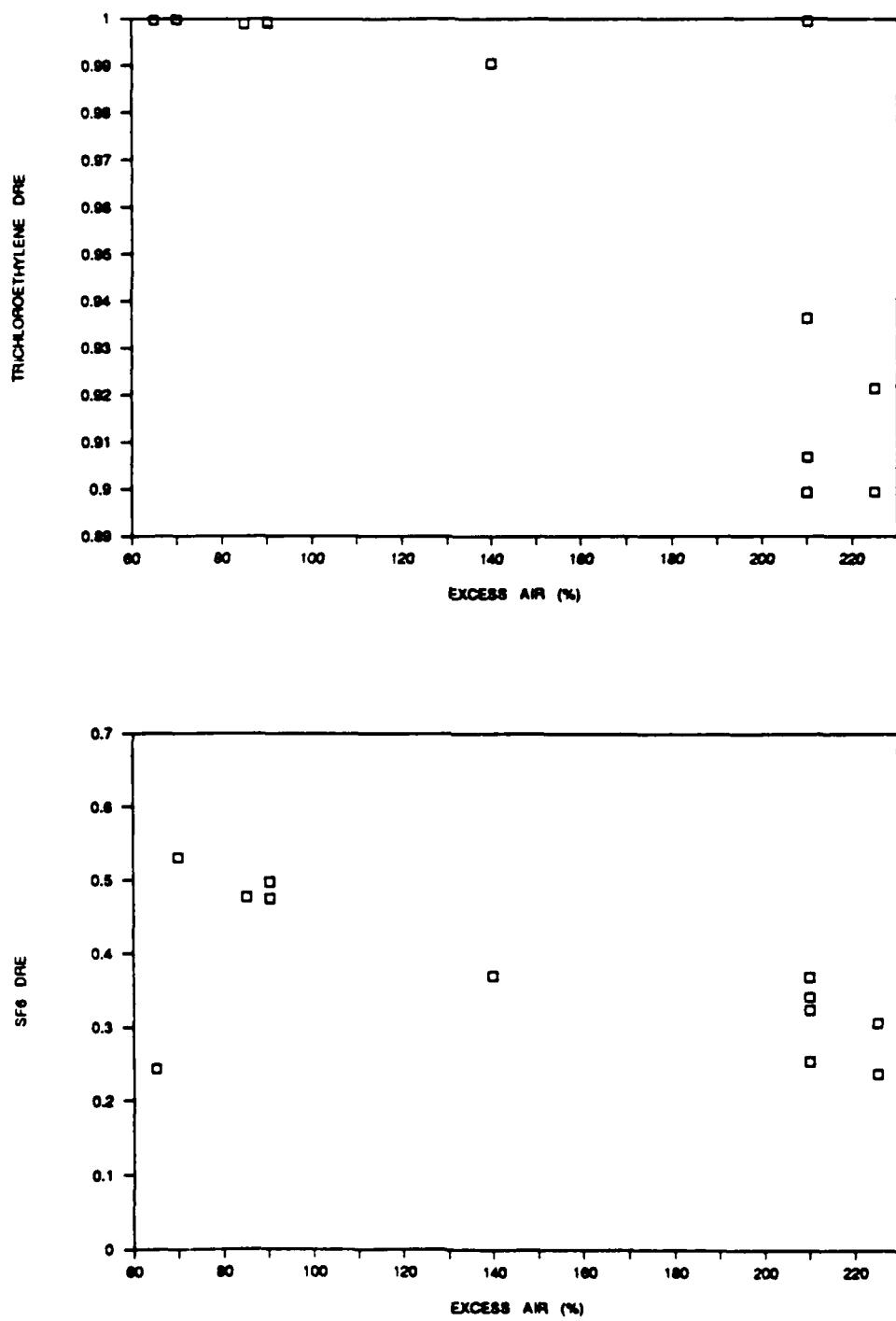


Figure 10. Trichloroethylene and Sulfur Hexafluoride DRE versus Excess Air for Liquid Fuel Firing in the Incineration Tunnel.

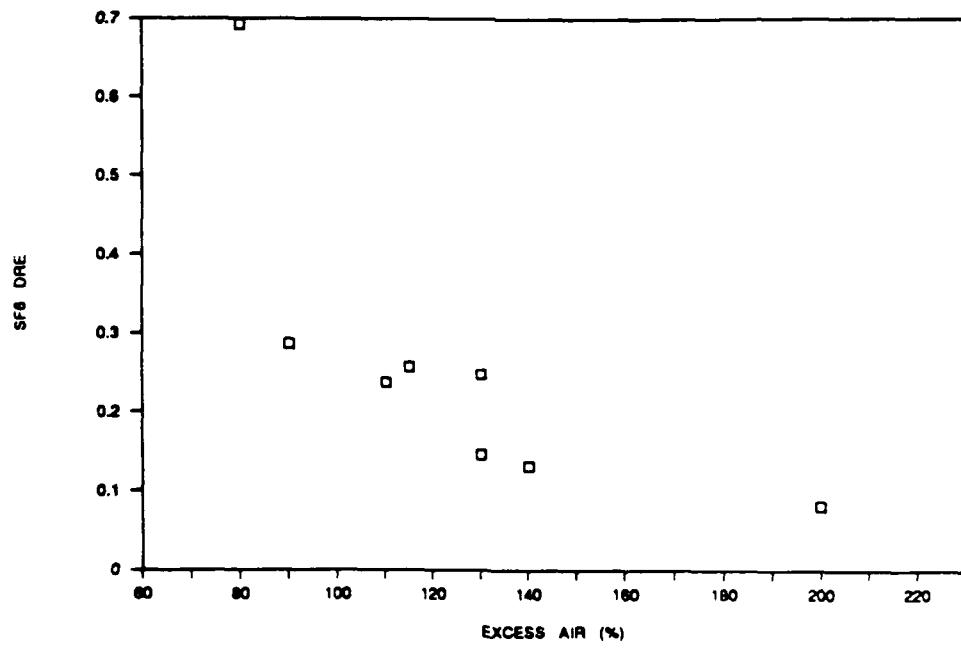
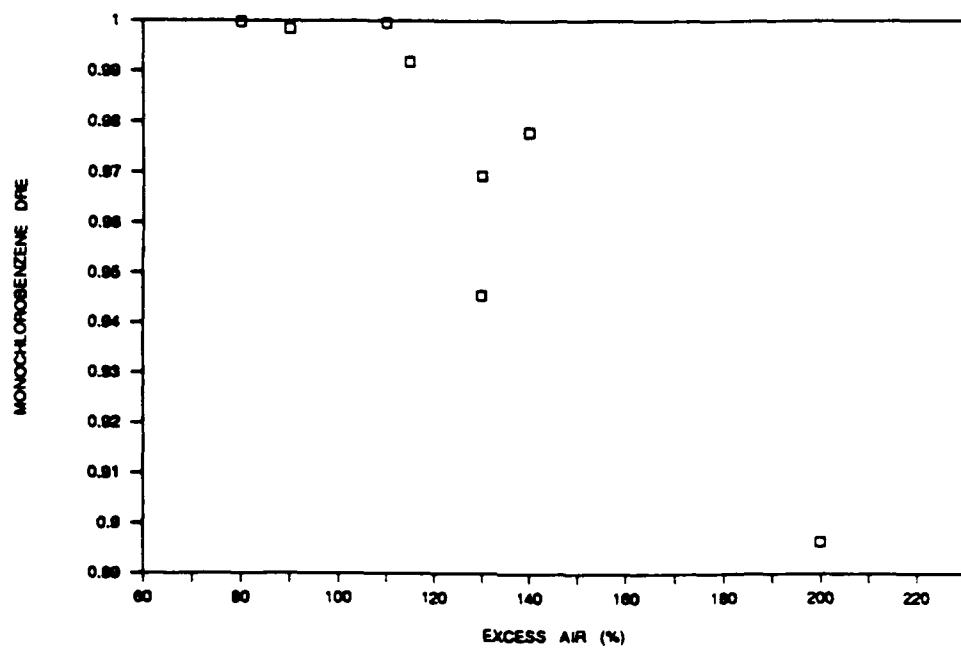


Figure 11. Monochlorobenzene and Sulfur Hexafluoride DRE versus Excess Air for Liquid Fuel Firing in the Incineration Tunnel.

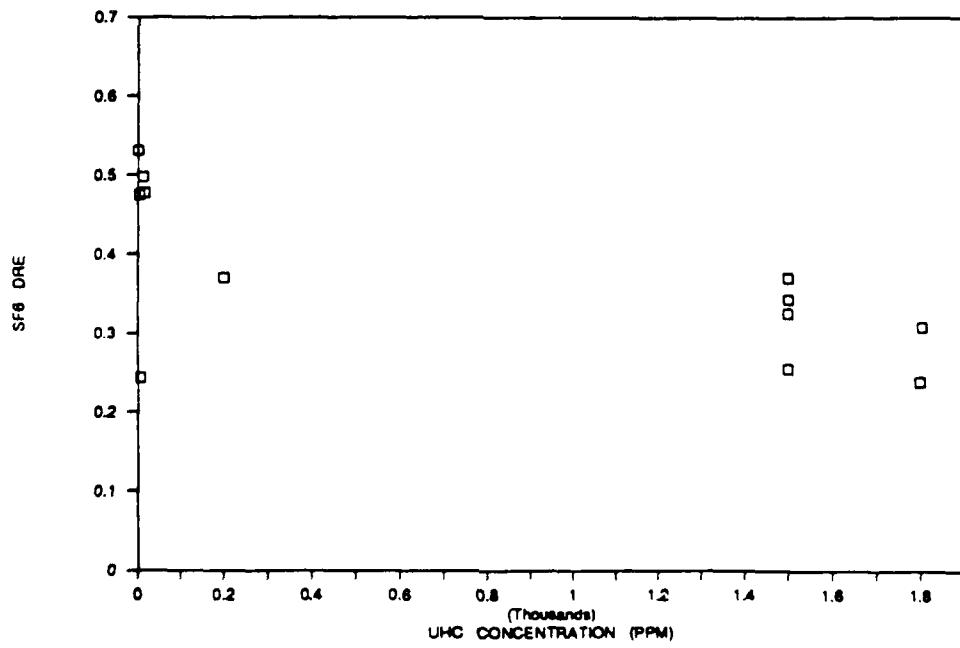
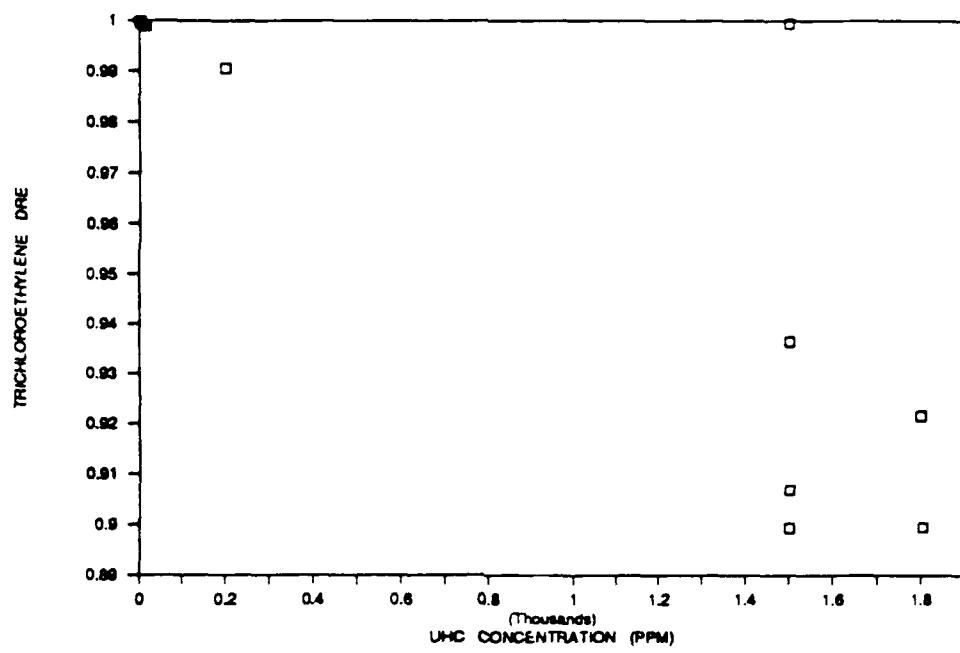


Figure 12. Trichloroethylene and Sulfur Hexafluoride DRE versus Exhaust Hydrocarbon Concentration for Liquid Fuel Firing in the Incineration Tunnel.

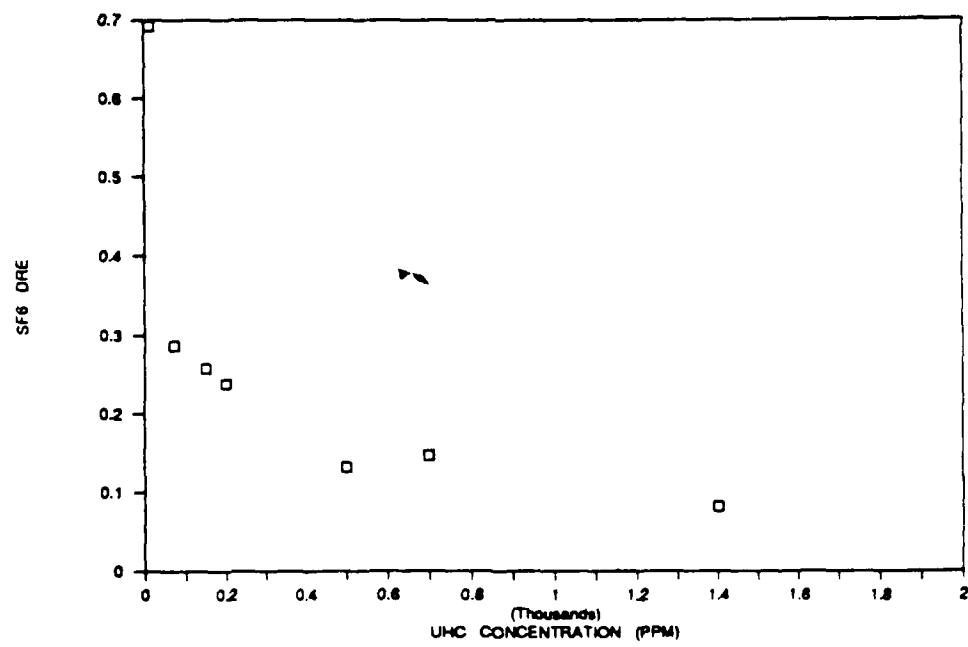
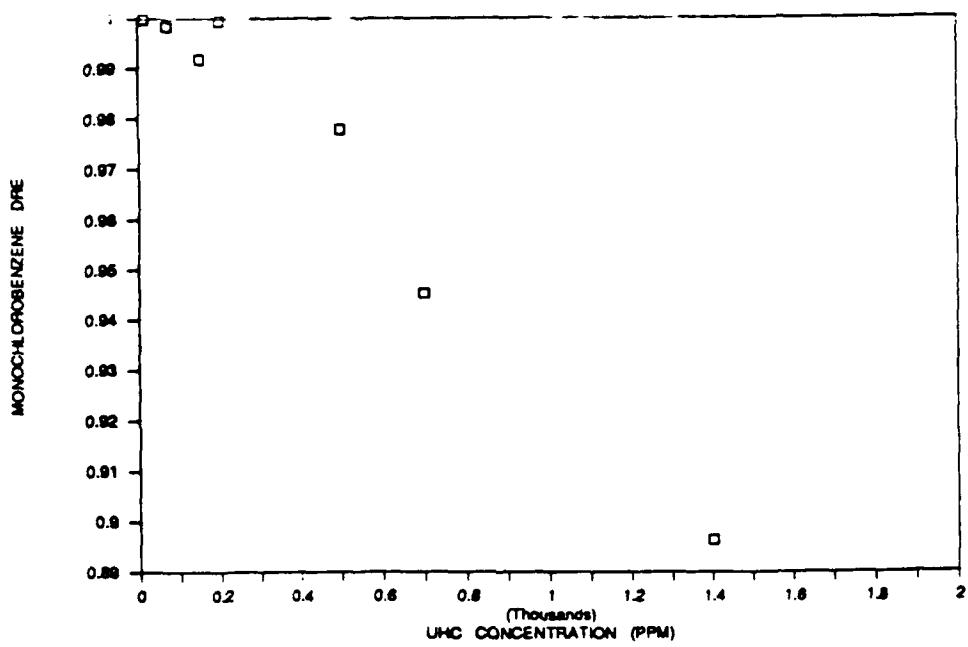


Figure 13. Monochlorobenzene and Sulfur Hexafluoride DRE versus Exhaust Hydrocarbon Concentration for Liquid Fuel Firing in the Incineration Tunnel.

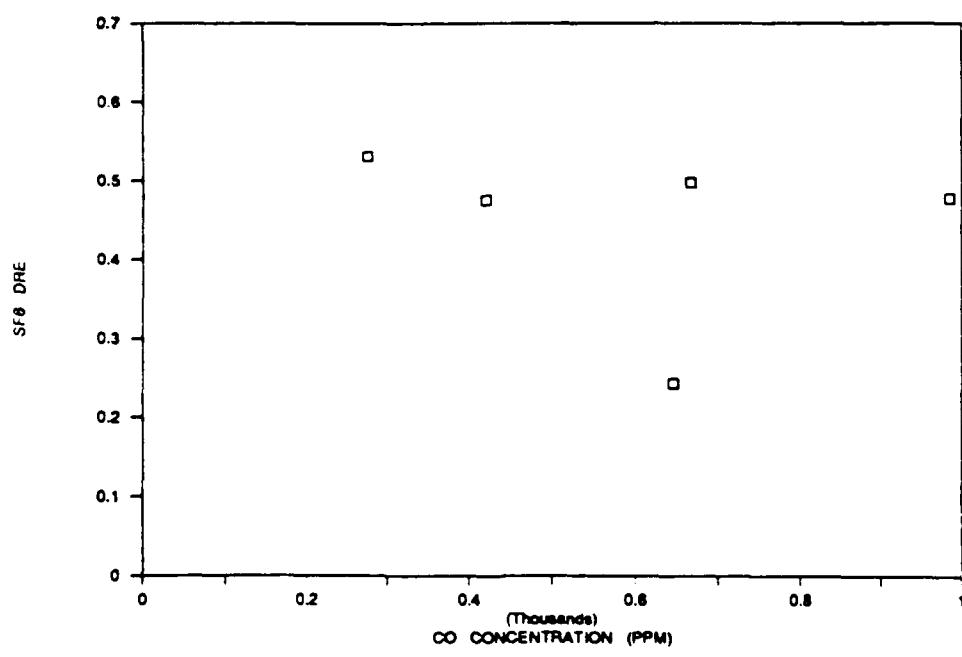
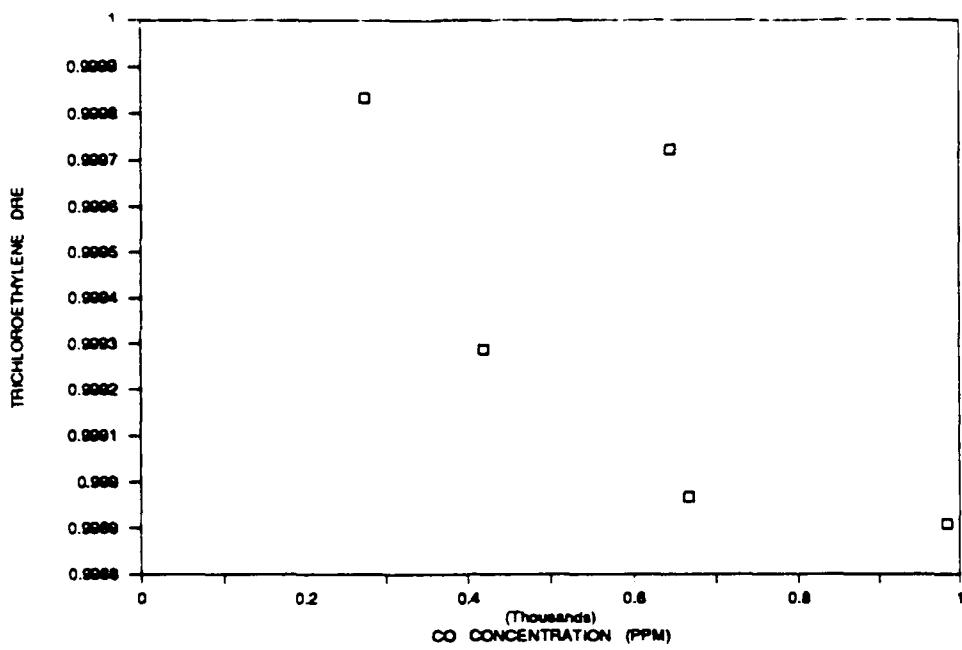


Figure 14. Trichloroethylene and Sulfur Hexafluoride DRE versus Exhaust CO Concentration for Liquid Fuel Firing in the Incineration Tunnel.

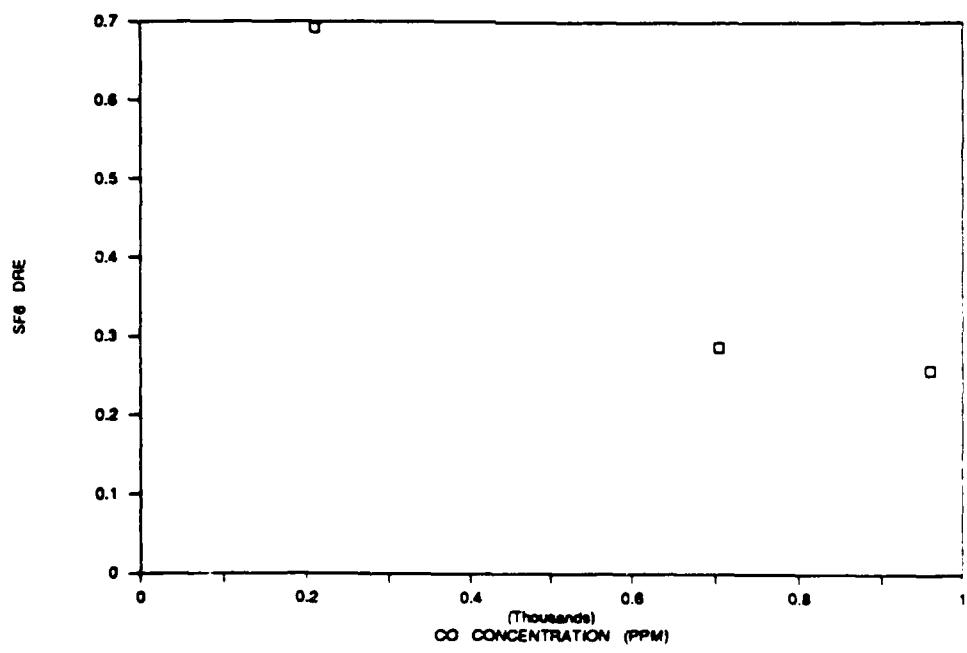
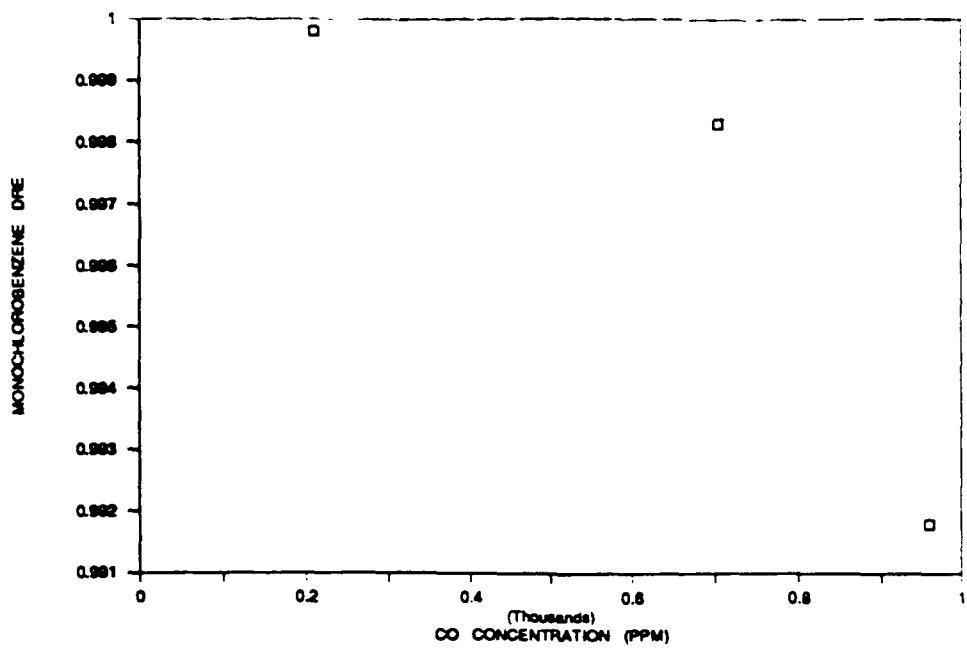


Figure 15. Monochlorobenzene and Sulfur Hexafluoride DRE versus Exhaust CO Concentration for Liquid Fuel Firing in the Incineration Tunnel.

The SF₆ exhaust concentrations ranged from 17.6 to 873 parts per billion. The electron capture detector of the gas chromatograph is sensitive to less than one part per billion. Therefore, these concentrations are excessively high for the run conditions used. However, running at optimal conditions would increase SF₆ DRE, requiring that the injection rate of SF₆ be adjusted accordingly. Table 4 also includes the concentration of waste in the fuel stream. Concentrations ranged from 14 to 49 percent for the chlorinated wastes, and 100 percent for the nonchlorinated wastes.

B. Incineration Tunnel and Steam Plant Boiler with Natural Gas

1. Data Analysis

The data analysis procedure used for the liquid waste runs was followed in analyzing the data from the natural gas runs in both the incineration tunnel and the steam plant boiler. The same assumptions were used. The Lotus spreadsheets for these runs are also included in the Appendix. A species balance was performed on the chemical equation of the form



where a, b, c and d are known from the natural gas and air flow rates. The total molar exhaust flow is given by e + f + g + h. SF₆ DRE was found using equations 1, 2 and 3.

The excess air and adiabatic flame temperature were calculated for each run. The adiabatic flame temperature was calculated using the chemical equilibrium solver STANJAN (Reference 57).

2. Results

The reduced data from the natural gas runs in the incineration tunnel and steam plant boiler are presented in Tables 5 and 6. Data from the continuous emission monitors were obtained only for the runs in the incineration tunnel and are presented in Table 7.

TABLE 5. REDUCED DATA FOR SF₆ BURNED WITH NATURAL GAS IN THE INCINERATION TUNNEL.

RUN #	FUEL FLOW kg/min	AIR FLOW kg/min	SF ₆ FLOW mg/min	SF ₆ IN EXHAUST ppb from GC	SF ₆ DRE	EQUI-VALENCE RATIO	EXCESS AIR	SF ₆ CONCENTRATION mg sf ₆ /kg fuel + air	INLET FLAME TEMP K	ADIABATIC
1	0.26	13	35	9.4	0.9798	0.34	195	2.4	1150	
2	0.26	9	35	5.6	0.9915	0.49	105	3.4	1445	
3	0.26	8	35	3.6	0.9951	0.54	85	3.8	1550	
4	0.26	7	35	2.8	0.9966	0.62	60	4.3	1680	
5	0.26	10	35	6.5	0.9895	0.46	120	3.2	1390	
6	0.10	13	35	54.2	0.8860	0.14	620	2.4	685	
7	0.10	10	35	35.7	0.9441	0.19	430	3.3	805	
8	0.10	9	35	27.5	0.9594	0.20	400	3.5	830	
9	0.10	8	35	19.9	0.9736	0.22	350	3.9	885	
10	0.10	7	35	22.0	0.9742	0.25	295	4.4	955	
11	0.20	13	35	15.3	0.9674	0.27	270	2.4	995	
12	0.20	10	35	10.4	0.9834	0.37	175	3.3	1200	
13	0.20	9	35	7.7	0.9884	0.39	160	3.5	1250	
14	0.20	8	35	4.7	0.9936	0.43	130	3.9	1340	
15	0.20	7	35	7.9	0.9905	0.49	105	4.3	1455	
16	0.20	7	35	5.9	0.9929	0.49	105	4.3	1455	

TABLE 6. REDUCED DATA FOR SF6 BURNED WITH NATURAL GAS IN UNIVERSITY OF FLORIDA STEAM PLANT, BOILER

RUN #	FUEL FLOW kg/min	AIR FLOW kg/min	SF6 FLOW mg/min	SF6 IN EXHAUST Ppb from GC	SF6 DRE	EQUI-VALENCE RATIO	EXCESS AIR %	SF6 CONCENTRATION mg sf6/kg fuel + air	ADIABATIC FLAME TEMP K
1	9.6	200	54	1.9	0.9568	0.82	20	0.23	2005
2	9.6	210	54	2.3	0.9453	0.78	30	0.22	1950
3	9.6	210	54	2.6	0.9382	0.78	30	0.22	1950
4	9.6	210	54	2.0	0.9524	0.78	30	0.22	1950
5	9.6	210	54	2.1	0.9500	0.78	30	0.22	1950
6	9.6	280	54	ND	>0.9970	0.59	70	0.17	1635
7	9.6	280	54	4.5	0.8611	0.59	70	0.17	1635
8	9.6	280	54	4.9	0.8488	0.59	70	0.17	1635
9	9.6	390	54	12.2	0.4816	0.42	140	0.12	1315
10	9.6	390	54	12.0	0.4901	0.42	140	0.12	1315
11	9.6	200	54	1.5	0.9659	0.82	20	0.23	2005
12	19.3	340	54	ND	>0.9961	0.98	2	0.14	2195
13	19.3	380	54	ND	>0.9957	0.87	15	0.12	2085
14	19.3	460	127	0.7	0.9846	0.71	40	0.24	1850
15	19.3	380	127	ND	>0.9957	0.87	15	0.29	2085
16	19.3	560	127	4.2	0.8901	0.60	70	0.20	1645
17	19.3	760	127	10.3	0.6389	0.44	130	0.15	1350
18	19.3	520	127	2.1	0.9480	0.63	60	0.21	1705
19	15.5	280	127	ND	>0.9986	0.95	5	0.39	2170
20	15.5	290	127	ND	>0.9986	0.92	10	0.38	2140
21	15.5	340	127	1.1	0.9819	0.78	30	0.32	1945
22	15.5	390	127	5.5	0.8984	0.69	45	0.28	1800
23	15.5	320	127	0.3	0.9953	0.82	20	0.34	2015
24	15.5	540	127	12.2	0.6926	0.49	105	0.21	1455
25	15.5	460	127	11.7	0.7453	0.58	75	0.24	1610

TABLE 7. DATA FROM CONTINUOUS EMISSION MONITORS FOR SF6 BURNED WITH NATURAL GAS IN THE INCINERATION TUNNEL.

RUN #	CO2 %	O2 %	CO ppm	UHC ppm	SF6 DRE
from continuous emission monitors					
1	4.3	13.0	246	30	0.9798
2	6.2	9.7	150	10	0.9915
3	6.6	9.5	94	1	0.9951
4	6.1	5.1	180	5	0.9966
5	5.9	10.2	96	5	0.9895
6	1.2	18.3	346	650	0.8860
7	1.6	17.6	224	250	0.9441
8	1.8	17.2	188	225	0.9594
9	2.0	16.9	163	195	0.9736
10	2.7	15.8	100	90	0.9742
11	2.6	15.7	284	160	0.9674
12	3.5	14.3	165	28	0.9834
13	4.0	13.4	100	9	0.9884
14	4.5	12.4	56	ND	0.9936
15	5.6	11.3	35	ND	0.9905
16	5.0	11.7	31	ND	0.9929

The exhaust SF₆ concentrations during the boiler experiment were at the low end of the detection limit. SF₆ was not detected in six runs and DREs for these runs were established based on a detection limit of 0.1 part per billion. This problem was caused by insufficient SF₆ inlet flow. Inlet concentrations in the incineration tunnel ranged from 2.4 to 4.4 milligrams SF₆ per kilogram of fuel plus air for the natural gas runs and 3.5 to 5.9 milligrams SF₆ per kilogram of fuel plus waste plus air for the liquid runs, but in the boiler the concentrations were only 0.15 to 0.39 milligrams SF₆ per kilogram fuel plus air. Based on the input flow of SF₆, the highest detectable DRE in the boiler was less than three nines. Higher SF₆ input flows should be used in future experiments.

Figures 16 and 17 show SF₆ DRE plotted against excess air in the incineration tunnel and the boiler. For both systems, SF₆ DRE falls with increased excess air. As with the liquid runs, there is insufficient data to determine whether the adverse effect on DRE by increased air flow is a result of reaction quenching (chemical kinetics) or reduced turbulent mixing effectiveness (fluid mechanics), or a combination of the two.

For a given excess air value the DREs in the boiler are lower than in the tunnel. During the boiler experiment the unit was involved in steam production. Much of the energy in the boiler was transferred to the waterwalls, while in the tunnel water flow through the last two sections was shut off. This extra available energy may be the reason for the higher DREs in the tunnel. The two systems also differ in size, surface-to-volume ratio and burner arrangement. Fluid mechanical differences between the two systems were not examined and may also be the reason for the differences in SF₆ DRE.

Data from the continuous emission monitors were only obtained for the runs in the incineration tunnel and are presented in Figures 18-21. Higher exhaust CO₂ concentrations correlate with higher SF₆ DRE. Increased exhaust concentrations of O₂ and unburned hydrocarbons are indicative of reduced SF₆ DRE. There is no strong correlation of exhaust CO with SF₆ DRE, although a trend of reduced DRE at higher CO concentrations is observed. These relations are similar to those observed for the liquid incineration runs.

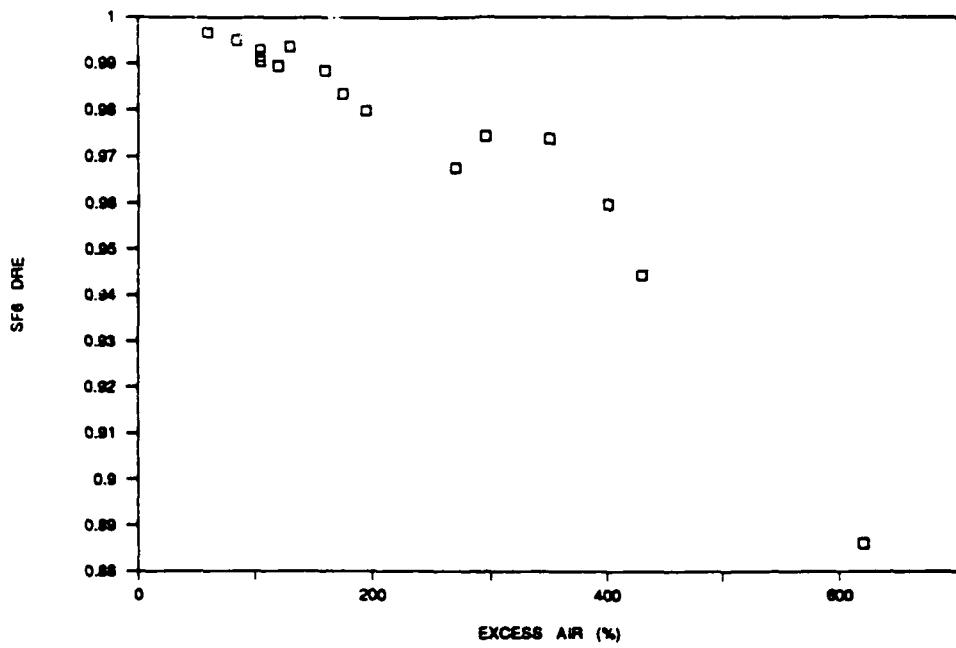


Figure 16. Sulfur Hexafluoride DRE versus Excess Air in the Incineration Tunnel Fired on Natural Gas.

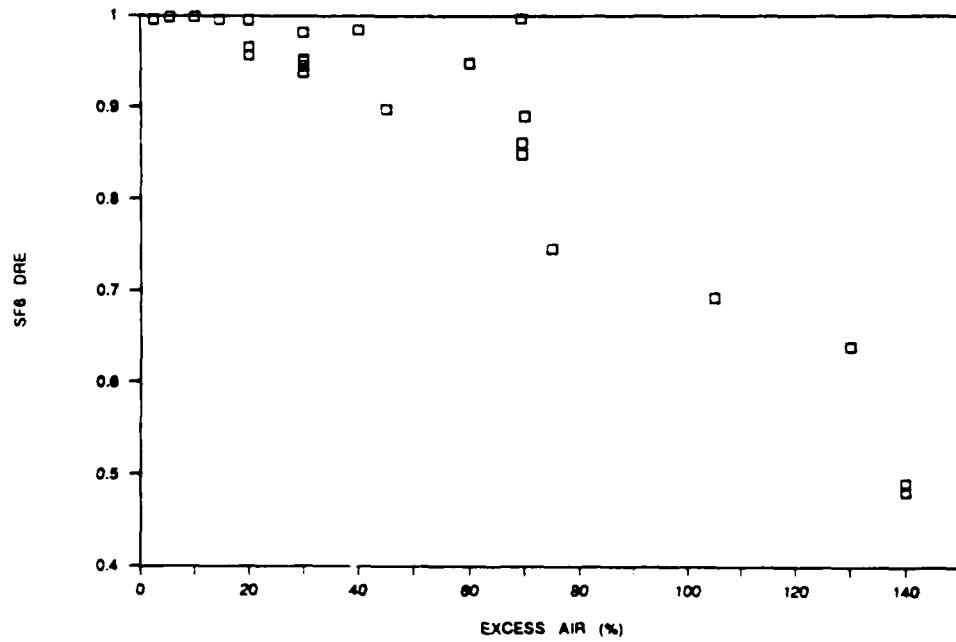


Figure 17. Sulfur Hexafluoride DRE versus Excess Air in the Steam Plant Boiler Fired on Natural Gas.

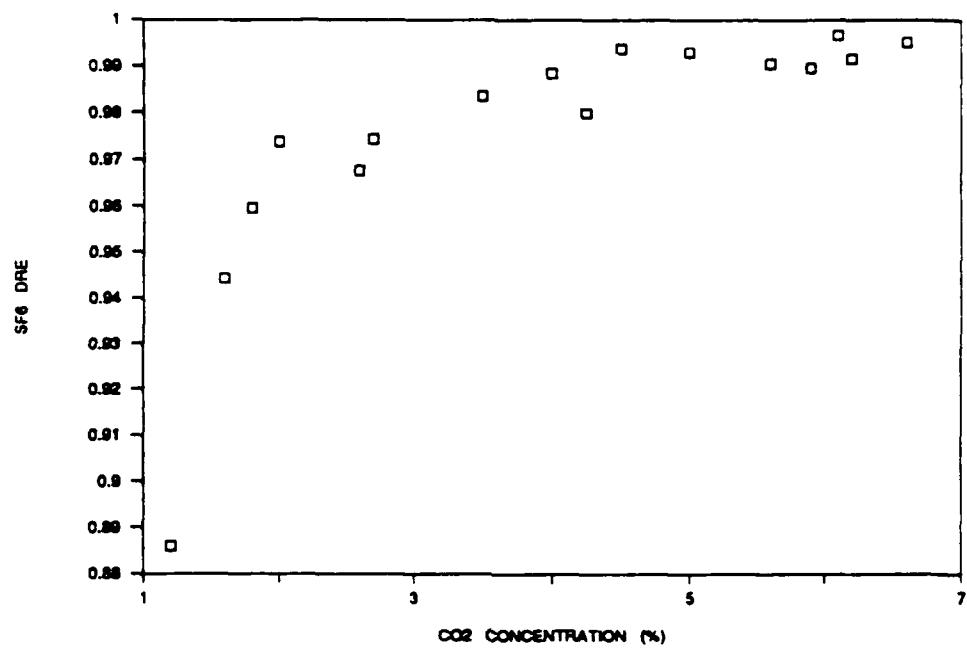


Figure 18. Sulfur Hexafluoride DRE versus Exhaust CO₂ Concentration in the Incineration Tunnel Fired on Natural Gas.

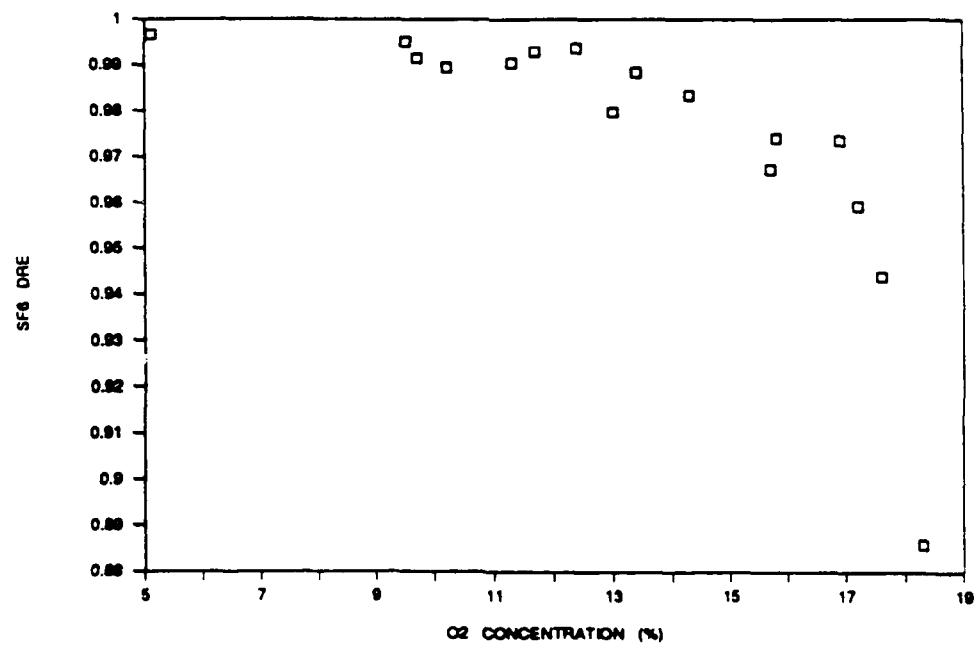


Figure 19. Sulfur Hexafluoride DRE versus Exhaust O₂ Concentration in the Incineration Tunnel Fired on Natural Gas.

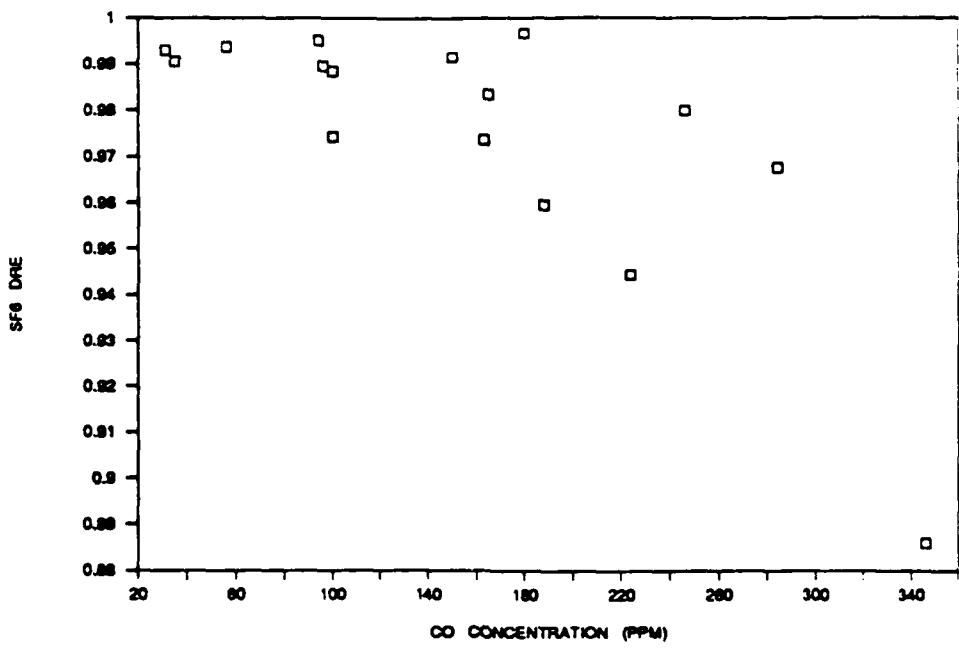


Figure 20. Sulfur Hexafluoride DRE versus Exhaust CO Concentration in the Incineration Tunnel Fired on Natural Gas.

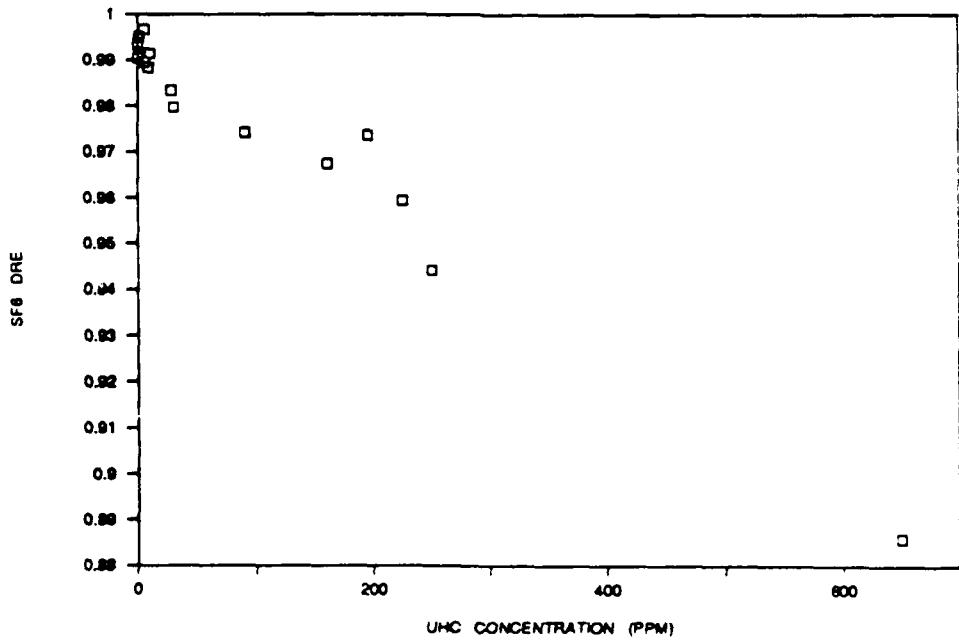


Figure 21. Sulfur Hexafluoride DRE versus Exhaust Hydrocarbon Concentration in the Incineration Tunnel Fired on Natural Gas.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This study compared exhaust gas emissions of CO, CO₂, O₂ and TUHC to the DRE of five hazardous wastes combusted in a pilot scale firetube boiler facility. Sulfur hexafluoride was added as a tracer and its DRE was compared to the DRE of the wastes and to the CO, CO₂, O₂ and TUHC emissions. SF₆ DRE was also compared to these exhaust emissions in the pilot scale facility fired on natural gas, and to excess air levels in a natural gas fired steam plant boiler.

The data obtained from the pilot scale facility indicate that toluene, methyl ethyl ketone and isopropanol are especially well-suited for destruction by incineration in a firetube boiler environment. Under all run conditions for these fuels waste emissions were below detection limits, indicating a minimum destruction of 99.997 percent.

Most of the data were obtained when burning trichloroethylene and monochlorobenzene, which were successfully detected in the exhaust on a near real-time basis. An auxiliary fuel was required when burning these chlorinated solvents to maintain stable combustion. This problem is recognized by the EPA, which limits the fraction of the fuel stream that may be waste.

SF₆ DRE was significantly lower than waste DREs for all runs. It also tracked the waste DREs during most runs, increasing with increased waste DREs and decreasing with decreased waste DREs.

Reduced waste and SF₆ DREs were accompanied by lower emissions of CO₂ and by increased emissions of O₂ and TUHC. DREs tended to fall with increased CO concentration, although too few data points were recorded to draw definite conclusions. DREs fell with excess air, especially for excess air above 100 percent. These patterns were also observed for SF₆ cofired with natural gas in the incineration tunnel facility. Finally, SF₆ DRE fell with increased excess air in the steam plant boiler.

The correlations between DREs and the data from the continuous emission monitors are better than reported by most investigators. One reason may be associated with the relatively low waste DREs which allowed near real time data collection and was not analytically taxing or complicated when compared to the typical modified method five or volatile organic sampling train methods. Another factor is the wide range of DREs obtained for the wastes, three orders of magnitude. Although the correlations

observed here are promising, they can only be of significant use if shown to occur at conditions corresponding to the high DREs required by law.

B. RECOMMENDATIONS

There are several other things that could be done with the data obtained during this study. The waste and SF₆ DREs could be compared to the energy content of each fuel-waste mixture. The energy content of the natural gas could be determined and compared with the liquid runs to help explain why the SF₆ DREs were lower during the runs with trichloroethylene and monochlorobenzene. Differences in the fluid mechanics between the liquid and gas fired modes could also be examined.

The DREs could be compared to the residence time in the incineration tunnel, and to the combustion efficiency expressed as CO/CO₂, or TUHC/CO₂. The GC and TUHC data could be used to estimate emissions of products of incomplete combustion.

Additional studies could be conducted in this facility to uncouple the effects of fluid mechanics and chemical kinetics on DRE. Residence time, temperature profiles, heat removal rate, turbulence and mixing characteristics could be examined and related to waste and SF₆ destruction.

The experimental data could be made more relevant to real-world environments by incorporating a volatile organic sampling train or a modified method five sampling train which would permit exhaust waste data collection when the unit is operating at optimum conditions. The greater sensitivity would also permit data collection over a wider range of operating conditions. Addition of a GC/MS system would allow studies on products of incomplete combustion.

Additional studies concerned with developing surrogate methods and tracers must be conducted in full scale-boilers and incinerators of various size and design, combusting a variety of wastes and fuels, under a wide range of operating conditions. Studies have found that these units can successfully destroy many wastes, but the increased use of incineration is limited by the expense associated with regulatory compliance and by public opposition.

Surrogates or tracers could reduce the permitting expense and increase the safety and public acceptance of waste incineration by providing a reliable real-time method of monitoring system performance. However, a conclusive data base from commercial facilities is required before the EPA can propose rules on the use of surrogates or tracers for verification of waste destruction. Additional studies with both SF₆ and continuous emission monitors is warranted by the results of this pilot-scale study.

APPENDIX
DATA ANALYSIS SPREADSHEETS

TRICHLOROETHYLENE DATA ANALYSIS.

A RUN #	B WASTE TYPE	C WASTE INPUT ml/min	D AIR INPUT cu m/min	E FUEL INPUT ml/min
1	TRICHLOR	62.50	8.26	403.80
2	TRICHLOR	62.50	8.26	403.80
3	TRICHLOR	117.65	8.26	403.80
4	TRICHLOR	62.50	8.26	448.00
5	TRICHLOR	117.65	8.26	448.00
6	TRICHLOR	62.50	8.26	315.30
7	TRICHLOR	62.50	8.26	241.60
8	TRICHLOR	62.50	8.26	241.60
9	TRICHLOR	62.50	8.26	241.60
10	TRICHLOR	62.50	8.26	241.60
11	TRICHLOR	22.64	8.26	241.60
12	TRICHLOR	22.64	8.26	241.60

F SF6 INPUT ml/min	G EXHAUST WASTE CONC., ppm	H EXHAUST SF6 CONC., ppb	I TRICHLOR IN kgmol/min
8.90	2.17	567.30	6.88E-04
8.90	1.50	593.10	6.88E-04
8.90	4.31	590.20	1.29E-03
8.90	0.35	527.40	6.88E-04
8.90	1.10	851.00	1.29E-03
8.90	20.03	716.50	6.88E-04
8.90	1.31	721.40	6.88E-04
8.90	135.72	772.40	6.88E-04
8.90	214.61	752.50	6.88E-04
8.90	198.65	852.60	6.88E-04
8.90	60.65	872.50	2.49E-04
8.90	77.60	792.60	2.49E-04

J AIR IN kgmol/min	K FUEL IN kgmol/min	L SF6 IN kgmol/min	M CALC. CO2 EXH. FLOW kgmol/min
3.11E-01	2.12E-03	3.70E-07	2.25E-02
3.11E-01	2.12E-03	3.70E-07	2.25E-02
3.11E-01	2.12E-03	3.70E-07	2.37E-02
3.11E-01	2.35E-03	3.70E-07	2.48E-02
3.11E-01	2.35E-03	3.70E-07	2.60E-02
3.11E-01	1.66E-03	3.70E-07	1.79E-02
3.11E-01	1.27E-03	3.70E-07	1.40E-02
3.11E-01	1.27E-03	3.70E-07	1.40E-02
3.11E-01	1.27E-03	3.70E-07	1.40E-02
3.11E-01	1.27E-03	3.70E-07	1.40E-02
3.11E-01	1.27E-03	3.70E-07	1.31E-02
3.11E-01	1.27E-03	3.70E-07	1.31E-02

N CALC. H2O EXH. FLOW kgmol/min	O CALC. O2 EXH. FLOW kgmol/min	P CALC. HCL EXH. FLOW kgmol/min	Q TOTAL EXH. FLOW kgmol/min
3.24E-02	2.66E-02	6.88E-04	3.27E-01
3.24E-02	2.66E-02	6.88E-04	3.27E-01
3.12E-02	2.59E-02	1.29E-03	3.27E-01
3.49E-02	2.30E-02	6.88E-04	3.29E-01
3.37E-02	2.24E-02	1.29E-03	3.29E-01
2.73E-02	3.37E-02	6.88E-04	3.25E-01
2.30E-02	3.97E-02	6.88E-04	3.23E-01
2.30E-02	3.97E-02	6.88E-04	3.23E-01
2.30E-02	3.97E-02	6.88E-04	3.23E-01
2.39E-02	4.01E-02	6.88E-04	3.23E-01
2.39E-02	4.01E-02	2.49E-04	3.23E-01
2.39E-02	4.01E-02	2.49E-04	3.23E-01

R WASTE EXH. FLOW kgmol/min	S SF6 EXH. FLOW kgmol/min	T WASTE DRE	U SF6 DRE
7.11E-07	1.86E-07	0.9990	0.4978
4.91E-07	1.94E-07	0.9993	0.4749
1.41E-06	1.93E-07	0.9989	0.4775
1.15E-07	1.73E-07	0.9998	0.5313
3.62E-07	2.80E-07	0.9997	0.2437
6.51E-06	2.33E-07	0.9905	0.3706
4.23E-07	2.33E-07	0.9994	0.3705
4.38E-05	2.49E-07	0.9363	0.3260
6.93E-05	2.43E-07	0.8993	0.3433
6.41E-05	2.75E-07	0.9068	0.2560
1.96E-05	2.82E-07	0.9214	0.2386
2.50E-05	2.56E-07	0.8995	0.3083

AS INLET CONC MASS SF6/TOTAL MASS IN mg/kg	AT TRICHLOR BREAKTHROUGH m(out)/m(in)	AU TRICHLOR UNCERTAINTY	AV PERCENT UNCERTAINTY TRICHLOR
5.75	0.0010	0.0003	25
5.7	0.0007	0.0002	25
5.71	0.0011	0.0003	26
5.73	0.0002	0.00004	26
5.69	0.0003	0.0001	26
5.79	0.0095	0.0024	25
5.83	0.0006	0.0002	25
5.83	0.0637	0.0159	25
5.83	0.1007	0.0251	25
5.83	0.0932	0.0233	25
5.86	0.0786	0.0195	25
5.86	0.1005	0.0249	25

AW SF6 BREAKTHROUGH m(out)/m(in)	AX SF6 UNCERTAINTY	AY PERCENT UNCERTAINTY SF6
0.5022	0.1079	21
0.5251	0.1128	21
0.5225	0.1123	21
0.4687	0.1004	21
0.7563	0.1619	21
0.6294	0.1358	22
0.6295	0.1365	22
0.6740	0.1462	22
0.6567	0.1424	22
0.7440	0.1613	22
0.7614	0.1649	22
0.6917	0.1499	22

AG AIR/FUEL ACTUAL	AH STOICH MOLES OF O2	AI STOICH MOLES OF N2	J AIR/FUEL STOICH
22.92	3.38E-02	1.27E-01	12.05
22.92	3.38E-02	1.27E-01	12.05
19.04	3.47E-02	1.30E-01	10.37
21.14	3.73E-02	1.40E-01	12.28
17.79	3.83E-02	1.44E-01	10.67
27.56	2.66E-02	1.00E-01	11.45
33.16	2.06E-02	7.75E-02	10.72
33.16	2.06E-02	7.75E-02	10.72
33.16	2.06E-02	7.75E-02	10.72
33.16	2.06E-02	7.75E-02	10.72
42.15	2.00E-02	7.50E-02	13.03
42.15	2.00E-02	7.50E-02	13.03

AK EQUIVALENCE RATIO	AL THEORETICAL AIR	AM EXCESS AIR	AN INLET MASS FUEL FLOW kg/min
0.53	190.26	90.26	3.00E-01
0.53	190.26	90.26	3.00E-01
0.54	183.61	83.61	3.00E-01
0.58	172.22	72.22	3.33E-01
0.60	166.69	66.69	3.33E-01
0.42	240.82	140.82	2.35E-01
0.32	309.40	209.40	1.80E-01
0.32	309.40	209.40	1.80E-01
0.32	309.40	209.40	1.80E-01
0.32	309.40	209.40	1.80E-01
0.31	323.57	223.57	1.80E-01
0.31	323.57	223.57	1.80E-01

AO INLET MASS AIR FLOW kg/min	AP INLET MASS WASTE FLOW kg/min	AQ INLET MASS SF6 FLOW kg/min	AR INLET CONC MASS SF6/TOT MASS IN (%)
9.01E+00	8.43E-02	5.40E-05	5.75E-04
9.01E+00	8.43E-02	5.40E-05	5.75E-04
9.01E+00	1.59E-01	5.40E-05	5.71E-04
9.01E+00	8.43E-02	5.40E-05	5.73E-04
9.01E+00	1.59E-01	5.40E-05	5.69E-04
9.01E+00	8.43E-02	5.40E-05	5.79E-04
9.01E+00	8.43E-02	5.40E-05	5.83E-04
9.01E+00	8.43E-02	5.40E-05	5.83E-04
9.01E+00	8.43E-02	5.40E-05	5.83E-04
9.01E+00	8.43E-02	5.40E-05	5.83E-04
9.01E+00	3.05E-02	5.40E-05	5.86E-04
9.01E+00	3.05E-02	5.40E-05	5.86E-04

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I8: (S2) +C8*1.10054*10^-5
J8: (S2) +D8*0.0376
K8: (S2) +E8*5.2546*10^-6
L8: (S2) +F8*4.156*10^-8
M8: (S2) 2*I8+9.95*K8
N8: (S2) 10.95*K8-2*I8+0.03383*J8
O8: (S2) 0.21*J8-M8-0.5*N8
P8: (S2) +I8
Q8: (S2) +M8+N8+O8+P8+0.79*J8
R8: (S2) +G8*Q8/10^6
S8: (S2) +H8*Q8/10^9
T8: (F4) 1-R8/I8
U8: (F4) 1-S8/L8
AG8: (F2) (32*J8*0.21+28*J8*0.79)/(141.59*K8+131.39*I8)
AH8: (S2) 1.5*I8+15.425*K8
AI8: (S2) 3.76*AH8
AJ8: (AH8*32+AI8*28)/(K8*141.59+122.56*I8)
AK8: +AJ8/AG8
AL8: 100/AK8
AM8: +AL8-100
AN8: (S2) +K8*141.59
AO8: (S2) +J8*29
AP8: (S2) +I8*122.56
AQ8: (S2) +L8*146.05
AR8: (S2) 100*AQ8/(AQ8+AP8+AO8+AN8)
AS8: 10000*AR8
AT8: (F4) +R8/I8
AU8: (F4) (((((3.4165*10^-3)*D8/C8)+((2.61*10^-6)*E8/C8)+2*10^-6)*0.1
AV8: (F0) +AU8*100/AT8
AW8: (F4) +S8/L8
AX8: (F4) (((((9.05*10^-4)*D8)+((6.92*10^-7)*E8)+C8*5.3*10^-7)*0.1*H8/F8)^2-
AY8: (F0) +AX8*100/AW8

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MONOCHLOROBENZENE DATA ANALYSIS.

A RUN #	B WASTE TYPE	C WASTE INPUT ml/min	D AIR INPUT cu m/min	E FUEL INPUT ml/min
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13	MCB	130.90	7.40	204.80
14	MCB	130.90	8.26	241.60
15	MCB	77.42	8.26	315.30
16	MCB	77.42	8.26	389.00
17	MCB	77.42	8.26	204.80
18	MCB	77.42	7.40	241.60
19	MCB	77.42	7.40	315.30
20	MCB	130.90	7.40	241.60

F SF6 INPUT ml/min	G EXHAUST WASTE CONC., ppm	H EXHAUST SF6 CONC., ppb	I MCB IN kgmol/min
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5.80	124.40	622.50	1.18E-03
5.80	198.10	632.90	1.18E-03
5.80	17.50	548.50	6.95E-04
5.80	0.50	226.00	6.95E-04
5.80	223.20	684.90	6.95E-04
5.80	52.70	718.50	6.95E-04
5.80	4.00	586.50	6.95E-04
5.80	2.00	628.90	1.18E-03

J AIR IN kgmol/min	K FUEL IN kgmol/min	L SF6 IN kgmol/min	M CALC. CO2 EXH. FLOW kgmol/min
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2.78E-01	1.08E-03	2.41E-07	1.78E-02
3.11E-01	1.27E-03	2.41E-07	1.97E-02
3.11E-01	1.66E-03	2.41E-07	2.07E-02
3.11E-01	2.04E-03	2.41E-07	2.45E-02
3.11E-01	1.08E-03	2.41E-07	1.49E-02
2.78E-01	1.27E-03	2.41E-07	1.68E-02
2.78E-01	1.66E-03	2.41E-07	2.07E-02
2.78E-01	1.27E-03	2.41E-07	1.97E-02

N CALC. H ₂ O kgmol/min	O CALC. O ₂ kgmol/min	P CALC. HCl kgmol/min	Q TOTAL EXH. FLOW kgmol/min
2.35E-02	2.89E-02	1.18E-03	2.91E-01
2.68E-02	3.22E-02	1.18E-03	3.25E-01
3.00E-02	2.95E-02	6.95E-04	3.26E-01
3.43E-02	2.36E-02	6.95E-04	3.28E-01
2.37E-02	3.85E-02	6.95E-04	3.23E-01
2.47E-02	2.93E-02	6.95E-04	2.91E-01
2.89E-02	2.33E-02	6.95E-04	2.93E-01
2.57E-02	2.59E-02	1.18E-03	2.92E-01

R WASTE EXH. FLOW kgmol/min	S SF ₆ EXH. FLOW kgmol/min	T WASTE DRE	U SF ₆ DRE
3.62E-05	1.81E-07	0.9692	0.2480
6.44E-05	2.06E-07	0.9452	0.1463
5.71E-06	1.79E-07	0.9918	0.2575
1.64E-07	7.42E-08	0.9998	0.6921
7.21E-05	2.21E-07	0.8963	0.0819
1.54E-05	2.09E-07	0.9779	0.1317
1.17E-06	1.72E-07	0.9983	0.2861
5.84E-07	1.84E-07	0.9995	0.2375

AG AIR/FUEL ACTUAL	AH STOICH MOLES OF O ₂	AI STOICH MOLES OF N ₂	AJ AIR/FUEL STOICH
27.07	2.51E-02	9.45E-02	11.63
27.66	2.81E-02	1.06E-01	11.91
28.01	3.06E-02	1.15E-01	13.13
23.91	3.66E-02	1.38E-01	13.40
37.70	2.16E-02	8.14E-02	12.50
30.28	2.46E-02	9.26E-02	12.76
25.09	3.06E-02	1.15E-01	13.13
24.78	2.81E-02	1.06E-01	11.91

AK EQUIVALENCE RATIO	AL THEORETICAL AIR	AM EXCESS AIR	AN INLET MASS FUEL FLOW kg/min
0.43	232.65	132.65	1.52E-01
0.43	232.13	132.13	1.80E-01
0.47	213.24	113.24	2.35E-01
0.56	178.41	78.41	2.89E-01
0.33	301.49	201.49	1.52E-01
0.42	237.38	137.38	1.80E-01
0.52	191.04	91.04	2.35E-01
0.48	207.96	107.96	1.80E-01

AO INLET MASS AIR FLOW kg/min	AP INLET MASS WASTE FLOW kg/min	AQ INLET MASS SF6 FLOW kg/min	AR INLET CONC MASS SF6/TOT MASS IN (%)
8.07E+00	1.44E-01	3.52E-05	4.21E-04
9.01E+00	1.44E-01	3.52E-05	3.77E-04
9.01E+00	8.52E-02	3.52E-05	3.77E-04
9.01E+00	8.52E-02	3.52E-05	3.75E-04
9.01E+00	8.52E-02	3.52E-05	3.81E-04
8.07E+00	8.52E-02	3.52E-05	4.22E-04
8.07E+00	8.52E-02	3.52E-05	4.20E-04
8.07E+00	1.44E-01	3.52E-05	4.19E-04

AS
INLET CONC
MASS SF6/TOTAL
MASS IN mg/kg

4.21
3.77
3.77
3.75
3.81
4.22
4.20
4.19

I31: (S2) +C31*8.983*10^-6
J31: (S2) +D31*0.0376
K31: (S2) +E31*5.2546*10^-6
L31: (S2) +F31*4.156*10^-8
M31: (S2) 6*I31+9.95*K31
N31: (S2) 10.95*K31+2*I31+0.03383*J31
O31: (S2) 0.21*J31-M31-0.5*N31
P31: (S2) +I31
Q31: (S2) +M31+N31+O31+P31+0.79*J31
R31: (S2) +G31*Q31/10^6
S31: (S2) +H31*Q31/10^9
T31: (F4) 1-R31/I31
U31: (F4) 1-S31/L31
AG31: (F2) (32*J31*0.21+28*J31*0.79)/(141.59*K31+122.56*I31)
AH31: (S2) 7.25*I31+15.425*K31
AI31: (S2) 3.76*AH31
AJ31: (AH31*32+AI31*28)/(K31*141.59+122.56*I31)
AK31: +AJ31/AG31
AL31: 100/AK31
AM31: +AL31-100
AN31: (S2) +K31*141.59
AO31: (S2) +J31*29
AP31: (S2) +I31*122.56
AQ31: (S2) +L31*146.05
AR31: (S2) 100*AQ31/(AQ31+AP31+AO31+AN31)
AS31: 10000*AR31

DATA ANALYSIS FOR INCINERATION TUNNEL ON NATURAL GAS.

A RUN #	B FUEL INPUT cu m/min	C AIR INPUT cu m/min	D SF6 INPUT ml/min
1	0.4233	11.85	5.8
2	0.4233	8.26	5.8
3	0.4233	7.40	5.8
4	0.4233	6.53	5.8
5	0.4233	8.78	5.8
6	0.1734	11.85	5.8
7	0.1734	8.78	5.8
8	0.1734	8.26	5.8
9	0.1734	7.40	5.8
10	0.1734	6.53	5.8
11	0.3375	11.85	5.8
12	0.3375	8.78	5.8
13	0.3375	8.26	5.8
14	0.3375	7.40	5.8
15	0.3375	6.53	5.8
16	0.3375	6.53	5.8

E INLET O2 FLOW cu m/min	F INLET N2 FLOW cu m/min	G INLET H2O FLOW cu m/min	H EXH CO2 FLOW cu m/min
2.49	9.36	0.18	0.42
1.73	6.53	0.12	0.42
1.55	5.85	0.11	0.42
1.37	5.16	0.10	0.42
1.84	6.94	0.13	0.42
2.49	9.36	0.18	0.17
1.84	6.94	0.13	0.17
1.73	6.53	0.12	0.17
1.55	5.85	0.11	0.17
1.37	5.16	0.10	0.17
2.49	9.36	0.18	0.34
1.84	6.94	0.13	0.34
1.73	6.53	0.12	0.34
1.55	5.85	0.11	0.34
1.37	5.16	0.10	0.34
1.37	5.16	0.10	0.34

I EXH N2 FLOW cu m/min	J EXH O2 FLOW cu m/min	K EXH H2O FLOW cu m/min	L TOTAL EXH FLOW cu m/min
9.36	1.64	1.02	12.45
6.53	0.89	0.97	8.81
5.85	0.71	0.96	7.93
5.16	0.52	0.94	7.05
6.94	1.00	0.98	9.34
9.36	2.14	0.52	12.20
6.94	1.50	0.48	9.09
6.53	1.39	0.47	8.56
5.85	1.21	0.46	7.68
5.16	1.02	0.44	6.80
9.36	1.81	0.85	12.37
6.94	1.17	0.81	9.25
6.53	1.06	0.80	8.72
5.85	0.88	0.79	7.85
5.16	0.70	0.77	6.97
5.16	0.70	0.77	6.97

M EXHAUST SF6 CONC., ppb	N SF6 EXH FLOW ml/min	O SF6 DRE	P ADIABATIC FLAME TEMPERATURE (K)
9.4	0.1170	0.9798	1148
5.6	0.0493	0.9915	1446
3.6	0.0286	0.9951	1552
2.8	0.0197	0.9966	1682
6.5	0.0607	0.9895	1390
54.2	0.6613	0.8860	683
35.7	0.3243	0.9441	804
27.5	0.2353	0.9594	832
19.9	0.1529	0.9736	887
22.0	0.1496	0.9742	956
15.3	0.1892	0.9674	997
10.4	0.0962	0.9834	1202
7.7	0.0672	0.9884	1250
4.7	0.0369	0.9936	1341
7.9	0.0550	0.9905	1453
5.9	0.0411	0.9929	1453

Q AIR/FUEL ACTUAL	R EQUIVALENCE RATIO	S THEORETICAL AIR	T EXCESS AIR
50.46	0.34	294.05	194.05
35.17	0.49	204.97	104.97
31.51	0.54	183.63	83.63
27.81	0.62	162.04	62.04
37.39	0.46	217.87	117.87
123.18	0.14	717.84	617.84
91.27	0.19	531.87	431.87
85.86	0.20	500.37	400.37
76.92	0.22	448.27	348.27
67.88	0.25	395.57	295.57
63.29	0.27	368.81	268.81
46.89	0.37	273.26	173.26
44.11	0.39	257.08	157.08
39.52	0.43	230.31	130.31
34.88	0.49	203.23	103.23
34.88	0.49	203.23	103.23

U INLET SF6 CONC BY MASS (%)	V SF6 INLET CONC mg SF6/Kg in	W SF6 FLOW kg/min	X AIR FLOW kg/min
2.42E-04	2.42	3.52E-05	12.92
3.44E-04	3.44	3.52E-05	9.00
3.83E-04	3.83	3.52E-05	8.07
4.32E-04	4.32	3.52E-05	7.12
3.24E-04	3.24	3.52E-05	9.57
2.45E-04	2.45	3.52E-05	12.92
3.29E-04	3.29	3.52E-05	9.57
3.50E-04	3.50	3.52E-05	9.00
3.90E-04	3.90	3.52E-05	8.07
4.41E-04	4.41	3.52E-05	7.12
2.43E-04	2.43	3.52E-05	12.92
3.26E-04	3.26	3.52E-05	9.57
3.46E-04	3.46	3.52E-05	9.00
3.85E-04	3.85	3.52E-05	8.07
4.35E-04	4.35	3.52E-05	7.12
4.35E-04	4.35	3.52E-05	7.12

Y
FUEL FLOW
kg/min

0.26
0.26
0.26
0.26
0.26
0.10
0.10
0.10
0.10
0.20
0.20
0.20
0.20
0.20
0.20

CELL FORMULAS FOR INCINERATION TUNNEL ON NATURAL GAS.

E7: (F2) 0.21*C7
F7: (F2) 0.79*C7
G7: (F2) 0.015*C7
H7: (F2) +B7
I7: (F2) +F7
J7: (F2) +E7-2*B7
K7: (F2) 2*B7+G7
L7: (F2) +H7+I7+J7+K7
M7: (F1) 9.4
N7: (F4) +M7*L7/1000
O7: (F4) 1-N7/D7
Q7: (F2) (32*0.21*C7+28*0.79*C7)/(B7*16)
R7: (F2) 17.16/Q7
S7: (F2) 100/R7
T7: (F2) +S7-100
U7: (S2) ((D7*10^-6)*146.05*100)/(B7*16+C7*29)
V7: (F2) +U7*10000
W7: +D7*6.07/10^6
X7: (F2) +C7*1.09
Y7: (F2) +X7/Q7

SF6 NATURAL GAS BURN IN UF BOILER #5.

A RUN #	B FUEL INPUT cu m/min	C AIR INPUT cu m/min	D SF6 INPUT ml/min
1	15.8	184	8.9
2	15.8	193	8.9
3	15.8	193	8.9
4	15.8	193	8.9
5	15.8	193	8.9
6	15.8	255	8.9
7	15.8	255	8.9
8	15.8	255	8.9
9	15.8	357	8.9
10	15.8	357	8.9
11	15.8	184	8.9
12	31.9	311	8.9
13	31.9	348	8.9
14	31.9	425	21.0
15	31.9	348	21.0
16	31.9	510	21.0
17	31.9	694	21.0
18	31.9	481	21.0
19	25.7	258	21.0
20	25.7	266	21.0
21	25.7	315	21.0
22	25.7	357	21.0
23	25.7	297	21.0
24	25.7	496	21.0
25	25.7	425	21.0

E INLET O2 FLOW cu m/min	F INLET O2 FLOW cu m/min	G INLET H2O FLOW cu m/min	H EXH CO2 FLOW cu m/min
39	145	2.8	15.8
41	152	2.9	15.8
41	152	2.9	15.8
41	152	2.9	15.8
41	152	2.9	15.8
54	201	3.8	15.8
54	201	3.8	15.8
54	201	3.8	15.8
75	282	5.4	15.8
75	282	5.4	15.8
39	145	2.8	15.8
65	246	4.7	31.9
73	275	5.2	31.9
89	336	6.4	31.9
73	275	5.2	31.9
107	403	7.7	31.9
146	548	10.4	31.9
101	380	7.2	31.9
54	204	3.9	25.7
56	210	4.0	25.7
66	249	4.7	25.7
75	282	5.4	25.7
62	235	4.5	25.7
104	392	7.4	25.7
89	336	6.4	25.7

65

I EXH N2 FLOW cu m/min	J EXH O2 FLOW cu m/min	K EXH H20 FLOW cu m/min	L TOTAL EXH FLOW cu m/min
145	7	34	203
152	9	34	212
152	9	34	212
152	9	34	212
152	9	34	212
201	22	35	275
201	22	35	275
201	22	35	275
282	43	37	378
282	43	37	378
145	7	34	203
246	2	68	348
275	9	69	385
336	25	70	463
275	9	69	385
403	43	71	550
548	82	74	736
380	37	71	520
204	3	55	288
210	4	55	296
249	15	56	345
282	24	57	388
235	11	56	327
392	53	59	529
336	38	58	457

M EXHAUST CONC., ppb	N SF6 EXH FLOW ml/min	O SF6 DRE	P ADIABATIC FLAME TEMPERATURE (K)
1.9	0.4	0.9568	2005
2.3	0.5	0.9453	1948
2.6	0.6	0.9382	1948
2.0	0.4	0.9524	1948
2.1	0.4	0.9500	1948
0.0	0.0	0.9970	1634
4.5	1.2	0.8611	1634
4.9	1.3	0.8488	1634
12.2	4.6	0.4816	1315
12.0	4.5	0.4901	1315
1.5	0.3	0.9659	2005
0.0	0.0	0.9961	2194
0.0	0.0	0.9957	2083
0.7	0.3	0.9846	1847
0.0	0.0	0.9957	2083
4.2	2.3	0.8901	1644
10.3	7.6	0.6389	1348
2.1	1.1	0.9480	1707
0.0	0.0	0.9986	2171
0.0	0.0	0.9986	2141
1.1	0.4	0.9819	1945
5.5	2.1	0.8984	1798
0.3	0.1	0.9953	2015
12.2	6.5	0.6926	1456
11.7	5.3	0.7453	1609

Q AIR/FUEL ACTUAL	R EQUIVALENCE RATIO	S THEORETICAL AIR	T EXCESS AIR
21.0	0.82	122.3	22.3
22.0	0.78	128.3	28.3
22.0	0.78	128.3	28.3
22.0	0.78	128.3	28.3
22.0	0.78	128.3	28.3
29.1	0.59	169.5	69.5
29.1	0.59	169.5	69.5
29.1	0.59	169.5	69.5
40.7	0.42	237.3	137.3
40.7	0.42	237.3	137.3
21.0	0.82	122.3	22.3
17.6	0.98	102.5	2.5
19.7	0.87	114.6	14.6
24.0	0.71	140.0	40.0
19.7	0.87	114.6	14.6
28.8	0.60	168.0	68.0
39.2	0.44	228.6	128.6
27.2	0.63	158.5	58.5
18.1	0.95	195.4	5.4
18.7	0.92	108.7	8.7
22.1	0.78	128.7	28.7
25.0	0.69	145.9	45.9
20.8	0.82	121.4	21.4
34.8	0.49	202.7	102.7
29.8	0.58	173.7	73.7

SF6 INLET CONC BY MASS (%)	U	V	W	X
	SF6 INLET CONC mg SF6/kg in		SF6 FLOW kg/min	AIR FLOW kg/min
2.33E-05		0.23	5.40E-05	200.6
2.22E-05		0.22	5.40E-05	210.4
2.22E-05		0.22	5.40E-05	210.4
2.22E-05		0.22	5.40E-05	210.4
2.22E-05		0.22	5.40E-05	210.4
1.70E-05		0.17	5.40E-05	278.0
1.70E-05		0.17	5.40E-05	278.0
1.70E-05		0.17	5.40E-05	278.0
1.23E-05		0.12	5.40E-05	389.1
1.23E-05		0.12	5.40E-05	389.1
2.33E-05		0.23	5.40E-05	200.6
1.36E-05		0.14	5.40E-05	339.0
1.23E-05		0.12	5.40E-05	379.3
2.39E-05		0.24	1.27E-04	463.3
2.89E-05		0.29	1.27E-04	379.3
2.00E-05		0.20	1.27E-04	555.9
1.49E-05		0.15	1.27E-04	756.5
2.12E-05		0.21	1.27E-04	524.3
3.89E-05		0.39	1.27E-04	281.2
3.77E-05		0.38	1.27E-04	289.9
3.21E-05		0.32	1.27E-04	343.4
2.85E-05		0.28	1.27E-04	389.1
3.40E-05		0.34	1.27E-04	323.7
2.07E-05		0.21	1.27E-04	540.6
2.41E-05		0.24	1.27E-04	463.3

Y
FUEL FLOW
kg/min

9.6
9.6
9.6
9.6
9.6
9.6
9.6
9.6
9.6
9.6
9.6
9.6
19.3
19.3
19.3
19.3
19.3
19.3
19.3
15.5
15.5
15.5
15.5
15.5
15.5
15.5
15.5

CELL FORMULAS FOR STEAM PLANT BOILER.

E7: (F0) 0.21*C7
F7: (F0) 0.79*C7
G7: (F1) 0.015*C7
H7: (F1) +B7
I7: (F0) +F7
J7: (F0) +E7-2*B7
K7: (F0) 2*B7+G7
L7: (F0) +H7+I7+J7+K7
M7: (F1) 1.9
N7: (F1) +M7*L7/1000
O7: (F4) 1-N7/D7
Q7: ((32*0.21*C7+28*0.79*C7)/(B7*16))
R7: (F2) 17.16/Q7
S7: 100/R7
T7: +S7-100
U7: (S2) ((D7*10^-6)*146.05*100)/(B7*16+C7*29)
V7: (F2) +U7*10000
W7: (S2) +D7*6.07/10^6
X7: +C7*1.09
Y7: +X7/Q7

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